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Heat Generation of Spent Bed Materials from Atmospheric Fluidized-Bed Combustion of Coal

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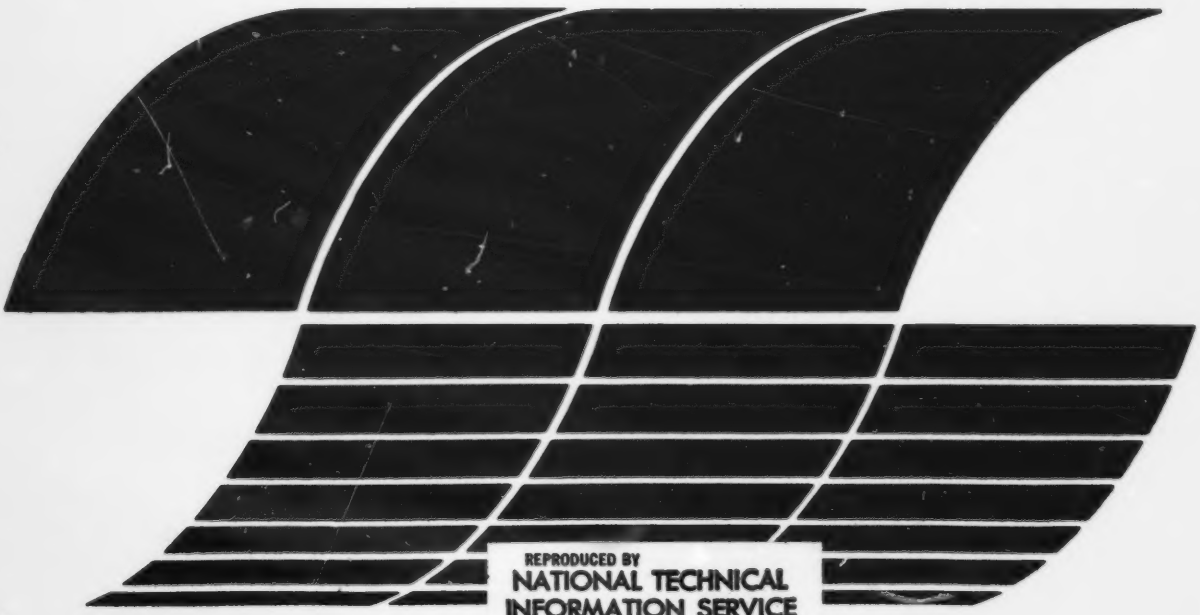
Interagency Energy/Environment R&D Program Report



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16. ABSTRACT The report describes an experimental investigation of the hydration process of spent bed material (with a calcium/sulfur ratio of 3) from an atmospheric fluidized bed combustor for maximum temperature, rate of temperature rise, and controllability of temperature rise with various amounts of water. Tap water was supplied through a rainfall simulating device. For the volume ration of the spent bed material to water larger than 1.2, the temperature of the spent bed material rose to 77 C; at ratios less than 1.2, the maximum temperature of the material was 132 C. Rates of temperature rise in the uncontrolled hydration process were higher than those in the controlled processes. The hydration process expanded the volume of the spent bed material faster than by moisture in the atmosphere when the material was exposed to the ambient atmosphere.

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Abstract

The hydration process of the spent bed material of the atmospheric fluidized-bed combustor, with a calcium-to-sulfur ratio of 3, was investigated for its maximum temperature, rate of temperature rise, and the controllability of the temperature rise with various quantities of water. Tap water was supplied through a rainfall simulating device. For the volume ratio of the spent bed material to water larger than 1.2, the temperature of the spent bed material rose to 77°C (170°F); at ratios less than 1.2, the maximum temperature of the material was 132°C (270°F). Rates of temperature rise in the uncontrolled hydration process were higher than those of the controlled hydration processes. The hydration process expanded the volume of the spent bed material faster than that caused by moisture in the atmosphere when the spent bed material was exposed to the ambient atmosphere.

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Introduction

A fluidized-bed combustor is a furnace in which pulverized coal and limestone are mixed with air and burned in a fluid-like consistency at atmospheric conditions. Calcined limestone captures sulfur dioxide in the furnace. Since the operating temperature of the furnace is only about 850°C (1562°F), atmospheric nitrogen is not fixed. The nitrogen oxides produced are from the nitrogen content of the coal only; thus the amount of nitrogen oxides produced are less than in conventional combustion. Particulates can be controlled by a properly designed baghouse. Recent studies have shown that the atmospheric fluidized-bed combustor (AFBC) would meet the current[1] and recently modified[2] new source performance standards. The AFBC would then be competitive with a furnace having a flue gas desulfurization device.

Solid residues exhausted from the bed would be in significant quantity since the AFBC would be used increasingly by industry and utilities.[3] Carry-over would increase considerably and hydration of quicklime may take place whether in temporary storage or in a landfill for permanent disposal of the solid bed material and carry-over. Hern et al.[4] reported that the solid bed residues have 27-38% of active Ca component. The hydration of quicklime is violent and releases a significant amount of heat.[5] An initial contact of the fluidized-bed combustor residues (FBCR) with water through a rainfall or runoff would create an unexpected change in the storage or in the landfill unless the FBCR is exposed to air for a long time, since the unused quicklime in the FBCR would undergo hydration, releasing heat and changing the structure of the components in the residues.

Stone[6] and Sun[7] have studied characteristics of the hydration process of the unused quicklime, and have found that the reaction of quicklime is a function of the solid residue to water ratio. They recognized the heat generation of quicklime as a future problem in storage or in the landfill operation when it is exposed to atmospheric moisture.

Purpose

The purpose of this study was to determine: (1) if there is a way to control a temperature rise due to the hydration process, and (2) if the method of constant head or constant flux for the hydraulic diffusion coefficient[8] is applicable to the transient unsaturated solid with moisture. In previous studies, the FBCR was contacted with water at a certain ratio of solid to water by weight or any arbitrary ratio in a container. The present experimental study simulates rainfall so that water drops penetrate the FBCR in a short column.

Conclusions

Short columns and a water holder for simulating rainfall were designed to measure rates of temperature rise as water dropped to the fluidized-bed combustor residue (FBCR) through the water holder holes. Simulation of rainfall appeared to be 5.08-10.16 cm (2-4 in.), equivalent to precipitation during the summer months. The flow rates were all very rapid, even when fine filter paper was used. Smaller holes in the base plate of the water holder, as originally planned, might have been more successful in controlling flow rate.

The maximum temperature of the FBCR, as it was hydrated, was about 132°C (270°F) at a depth of 10.16 cm (4 in.) and deeper from the surface of the FBCR. The quantity of water needed to control the FBCR below 77°C (170°F) in the hydration process was 1500 cm^3 for 1800 cm^3 of the FBCR.

The rates of temperature rise seemed to be of two types: a slow rate for controlling the FBCR to 77°C (170°F), and a fast rate for uncontrolled hydration processes. At either rate, the volume of the FBCR expanded.

Recommendations

1. Improvement of the water holder. The holes in the base plate of the water holder were 0.1588 cm (1/16-in.) in diameter. It is now recommended that 0.0794 cm (1/32-in.) in diameter holes be used, so flow rates can be better controlled using the level adjuster of the water holder.

2. A wide range of flow rates is recommended, using a number of base plates with different size holes. The base plate should be bolted against a gasket on the side plates.

3. The column for controlling temperature rise should be scaled up by keeping the volume ratio of rainfall to the FBCR constant (approximately 8/9).

4. Longer time duration (more than 3 hours) for a volume expansion should be tried for complete expansion.

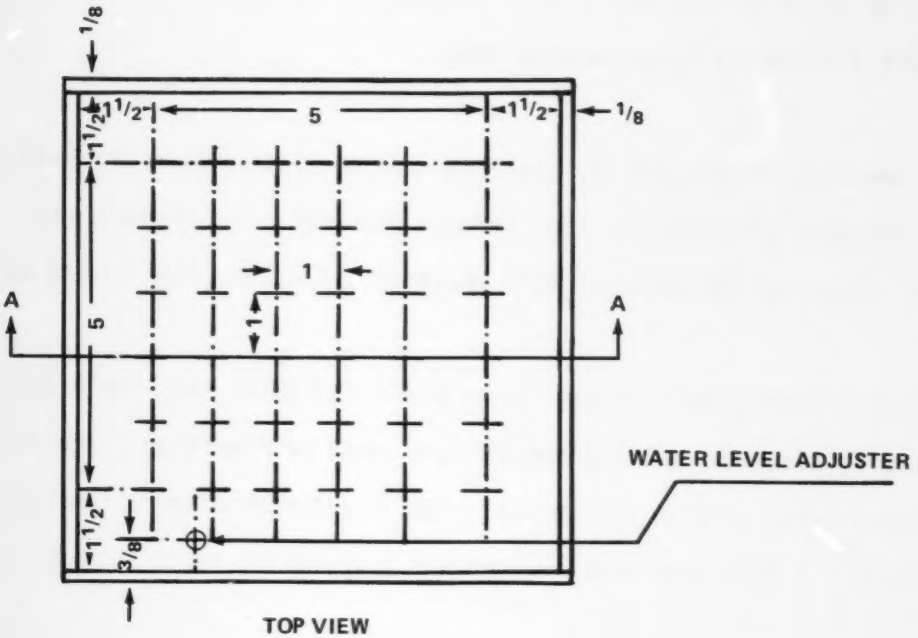
5. The thermal diffusivity of the FBCR having various moisture contents is recommended for a measurement. By doing so, a numerical solution for a temperature distribution (while the hydraulic diffusion takes place) is possible.

6. Chemical composition of the FBCR before and after hydration is recommended for a further study, using X-ray defraction or a scanning electronmicroscope.

Design of Apparatus

Recently, the activity of FBCR has been studied experimentally. Water was poured in a glass or plastic container containing FBCR[6,7]. In usual landfills or storage of FBCR, initial contact between the FBCR and water is through infiltration of rainfall. Atmospheric moisture affects the FBCR very slowly; the hydration process may generate hardly any heat; however, it may change the chemical structure of the unused calcined lime and calcium sulfate, thus increasing volume of the FBCR. Simulation of rainfall on the FBCR in a container is more "natural" than pouring water on the FBCR in the container. The rainfall simulation apparatus consisted of a water holder, a short square column, and other apparatus.

1. Water holder (see Figure 1). Once rain starts penetrating through the FBCR, the water flow is one dimensional in an almost vertical plane. The penetration of water is observed through a 15.24 x 15.24 cm (6 x 6 in.) base and 30.48 cm (12 in.) high column. An even distribution of water flow is sought from the water holder. The water holder base is a square piece of Plexiglas: 20.3 cm (8 in.) on a side and 1.27 cm (1/2-in.) thick. Thirty-six holes (0.16 cm OD, 1/16-in.) are drilled so that each hole covers a 2.54 cm^2 (1 $in.^2$) area when water passes through the holes through the base of the water holder. On one side near the base, is a 0.64 cm (1/4-in.) OD Plexiglas tube. The height adjustment of the tube above the base determines the constant head of water in the holder, giving a steady flow rate. The side plates are glued to the base with epoxy resin.



UNIT EQUIVALENTS

in.	cm
1/8	0.318
3/8	0.953
1	2.54
1 1/2	3.81
5	12.70

(All units are inches)

Figure 1. Water holder (not to scale).

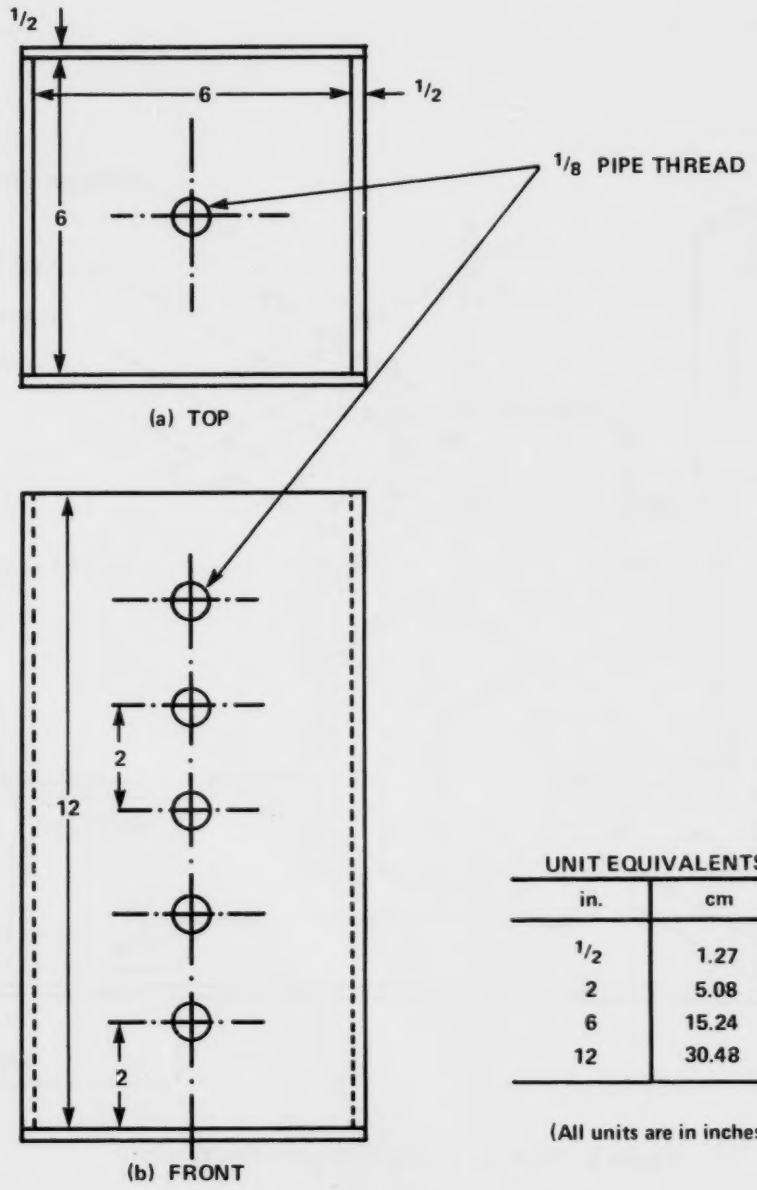
2. Short square column (see Figure 2). The original short square column was Plexiglas with inside dimensions of 15.24 x 15.24 x 30.48 cm (6 x 6 x 12 in.). Each pair of edges is glued together with epoxy which would retain its strength up to 310°C (500°F). The edges are fastened additionally by bolts at 5.08 cm (2 in.) intervals. An opening in the base has a Swagelok fitting for a connecting tube.

On one side of the plates, starting 5.08 cm (2 in.) from the base plate, are six Swagelok adapters for the thermocouples and a U-tube manometer. Properly adjusting the Swagelok nuts prevents the column from losing water.

Results from several initial experiments indicated that the highest temperature rise is above the molding temperature range of Plexiglas. The midsection square cross-section column was slightly deformed after a few hydration experiments. A stainless steel column was prepared to avoid this deformation.

The cylindrical stainless steel container (shown in the inset of Figure 3) is 16.5 cm (6-1/2 in.) in diameter and 15.87 cm (7-5/8 in.) high; it had four thermocouple adapters, one above the other. The adapters are 5.08 cm (2 in.) apart; the bottom one is 2.54 cm (1 in.) above the base.

In order to simulate rainfall on the FBCR placed in a column, the water holder was put aside until steady flow was established using a peristaltic pump and slowly moving the turning arm which supports the water holder with a holder base. See Figure 3.



UNIT EQUIVALENTS	
in.	cm
1/2	1.27
2	5.08
6	15.24
12	30.48

(All units are in inches)

Figure 2. Short square column (not to scale).

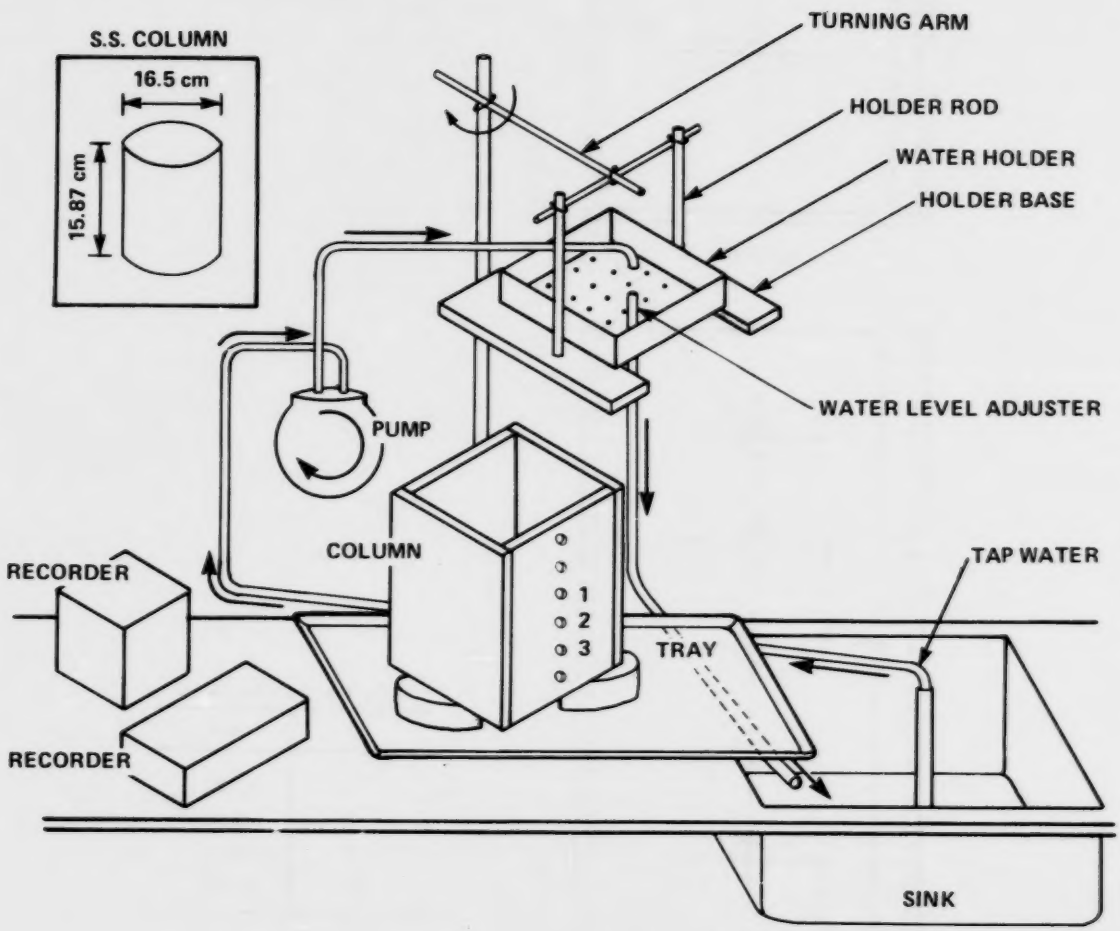


Figure 3. Short column and its operating system.

The initial experiments indicated that 36 holes of the water holder provide excessive flow rates when they are compared with an average rainfall of the West Virginia area.[9]. Several filter paper types were used to cover the holes. It turned out that the longer term use of filter paper yielded greater flow rates; flow rates with filter paper were proportional to time. A few plots of flow rates vs. time were made. Within the limit of applications, flow rates changed linearly with time. See Figures 4-14. Flow rates were also controlled by covering 20 outer holes. The quantity of water for each experiment was determined by the average flow rate from the flow rate vs time diagram. Accuracies of the flow rates are estimated to be $\pm$5 percent.

3. Other apparatus. Other apparatus used in the experiments include:

   a. Angus Temperature Recorder with K-type thermocouples.

   b. Cole-Palmer Two-Pen Recorder with 1 mv attenuator capability.

   c. K-type thermocouples with OMEGA-CJ reference junction compensators. Time constant of the thermocouple is on the order of 1 second. Accuracy of the thermocouple is in the range of -17 to -15°C (2-5°F).

   d. Electronic scale (to four decimal places).

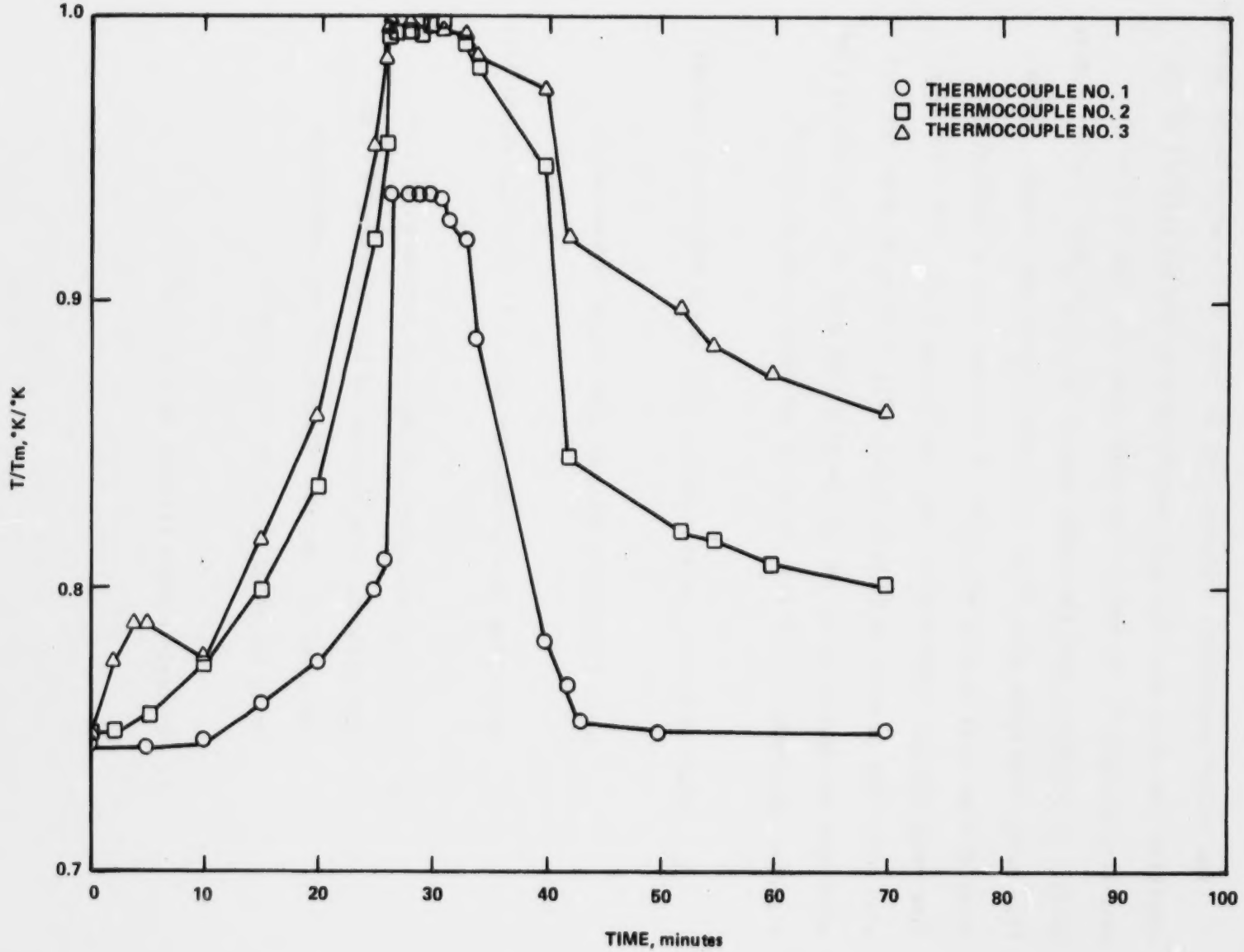


Figure 4. Temperature history of run No. 1.

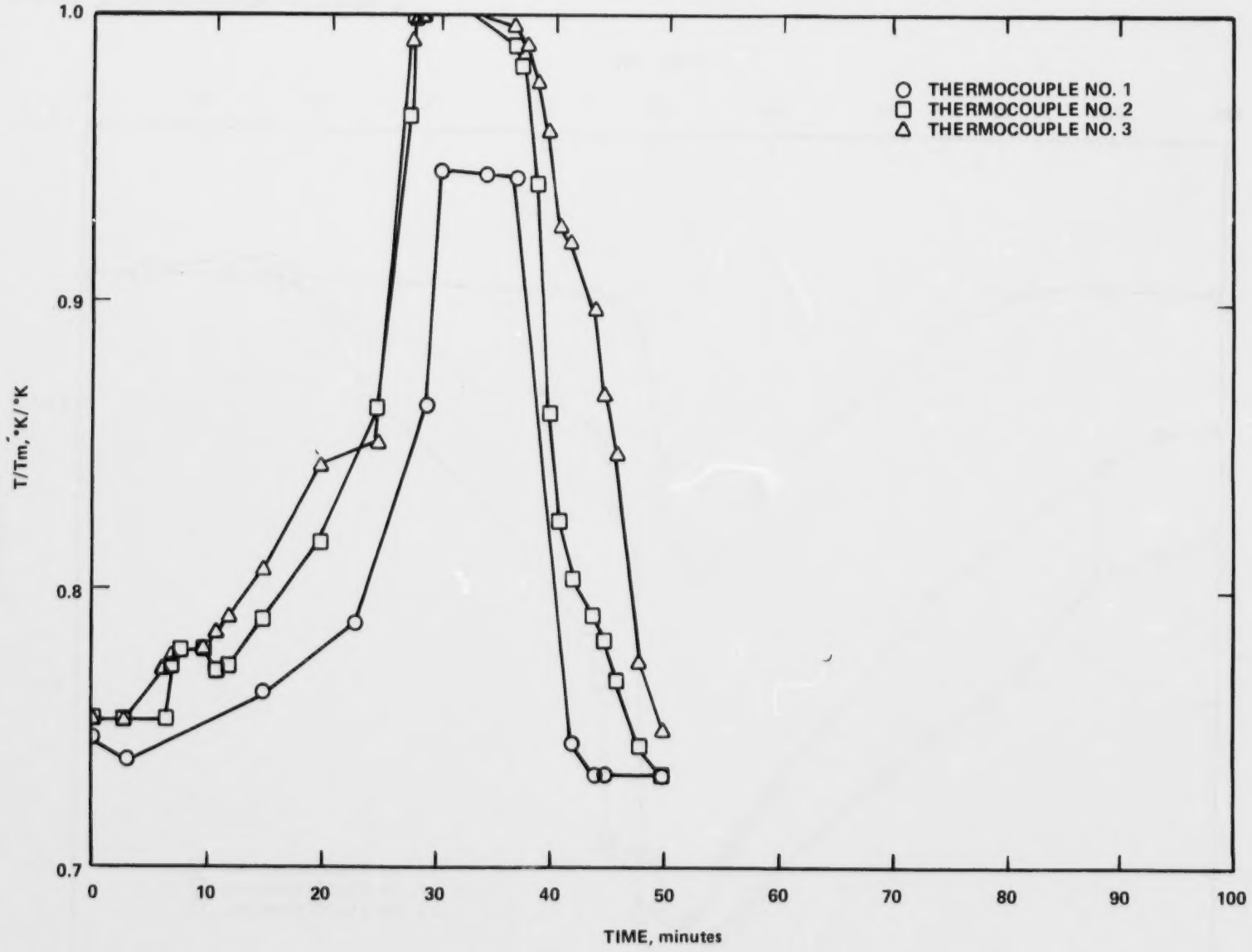


Figure 5. Temperature history of run No. 2.

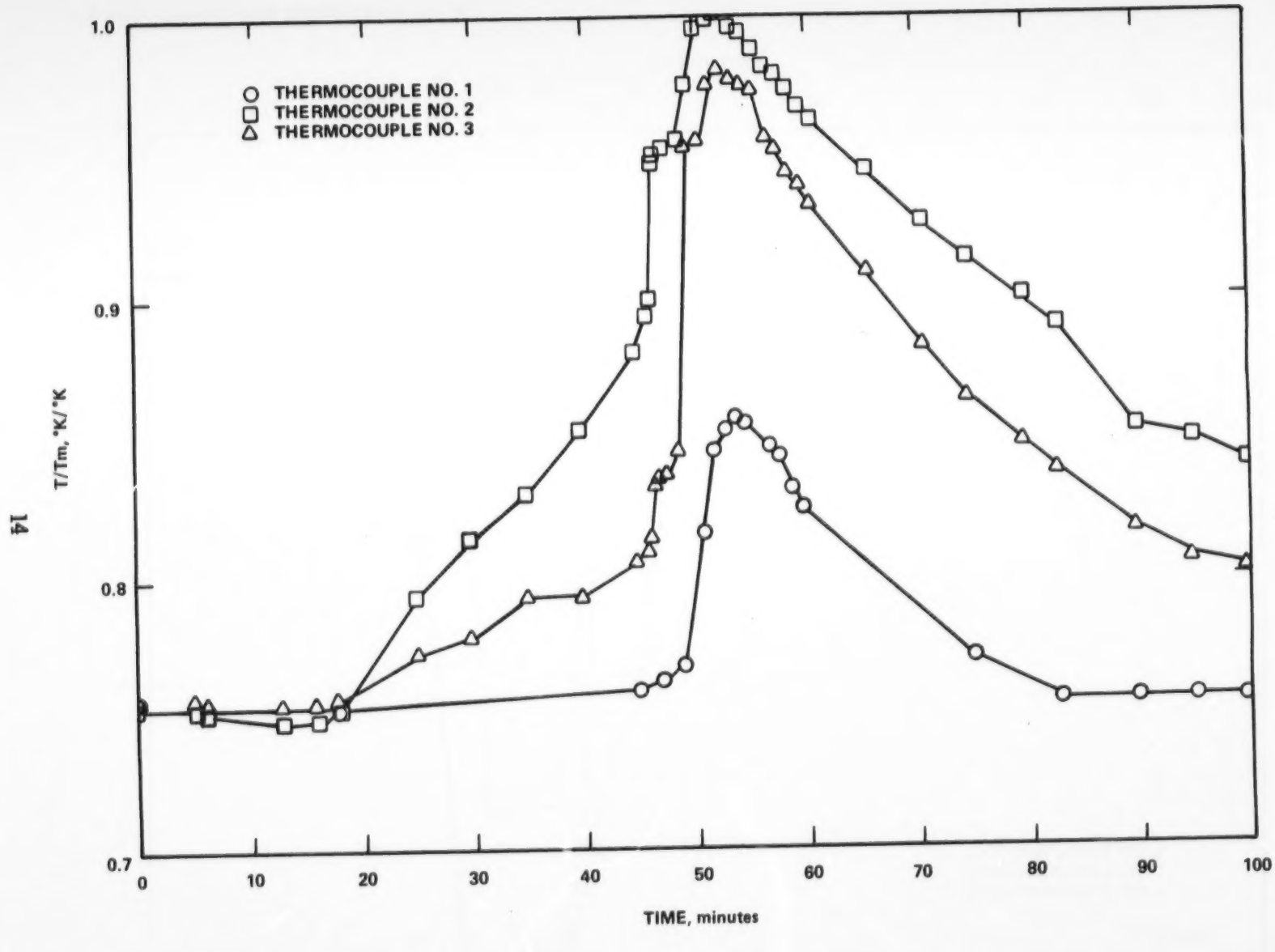


Figure 6. Temperature history of run No. 3.

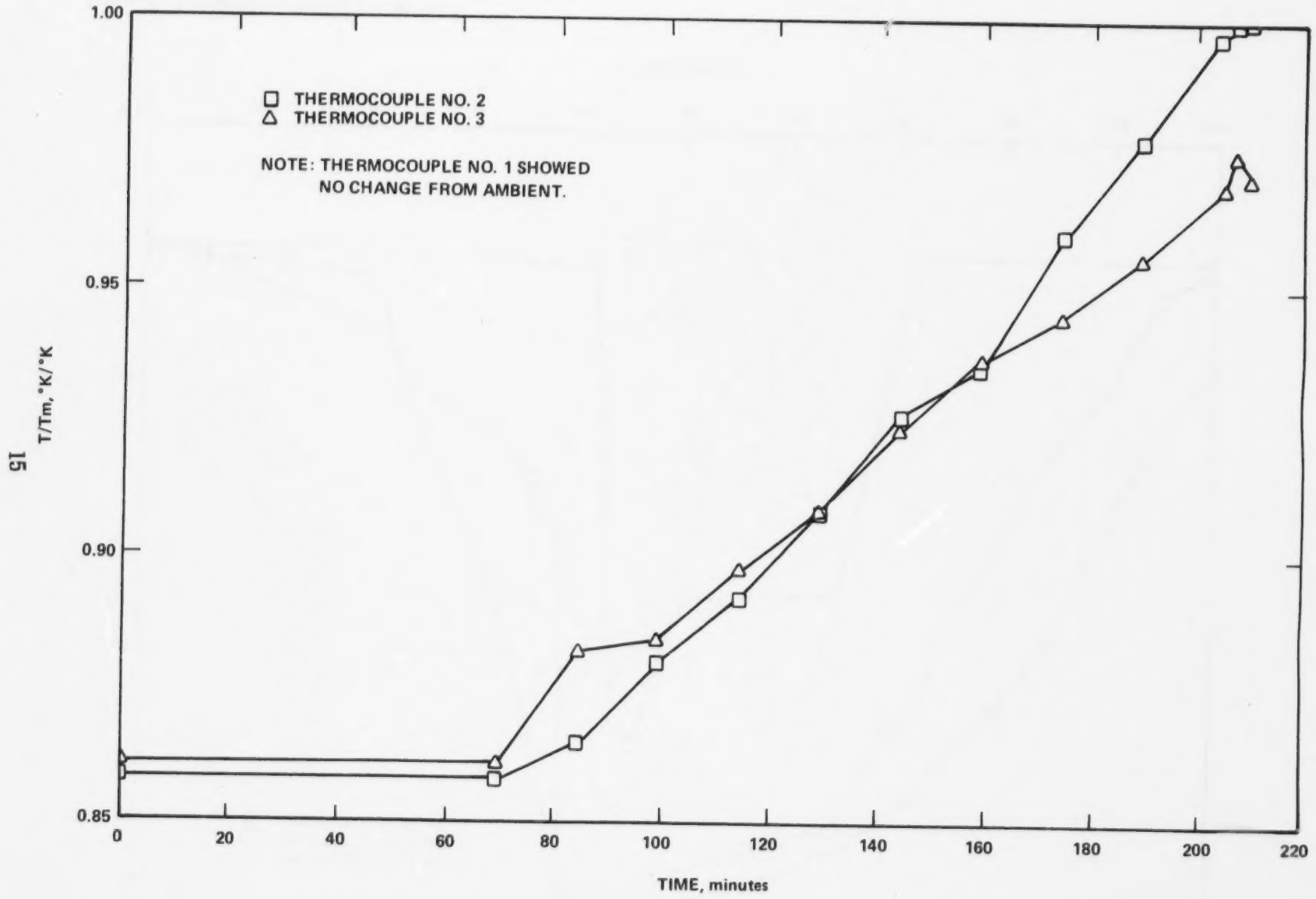


Figure 7. Temperature history of run No. 4.

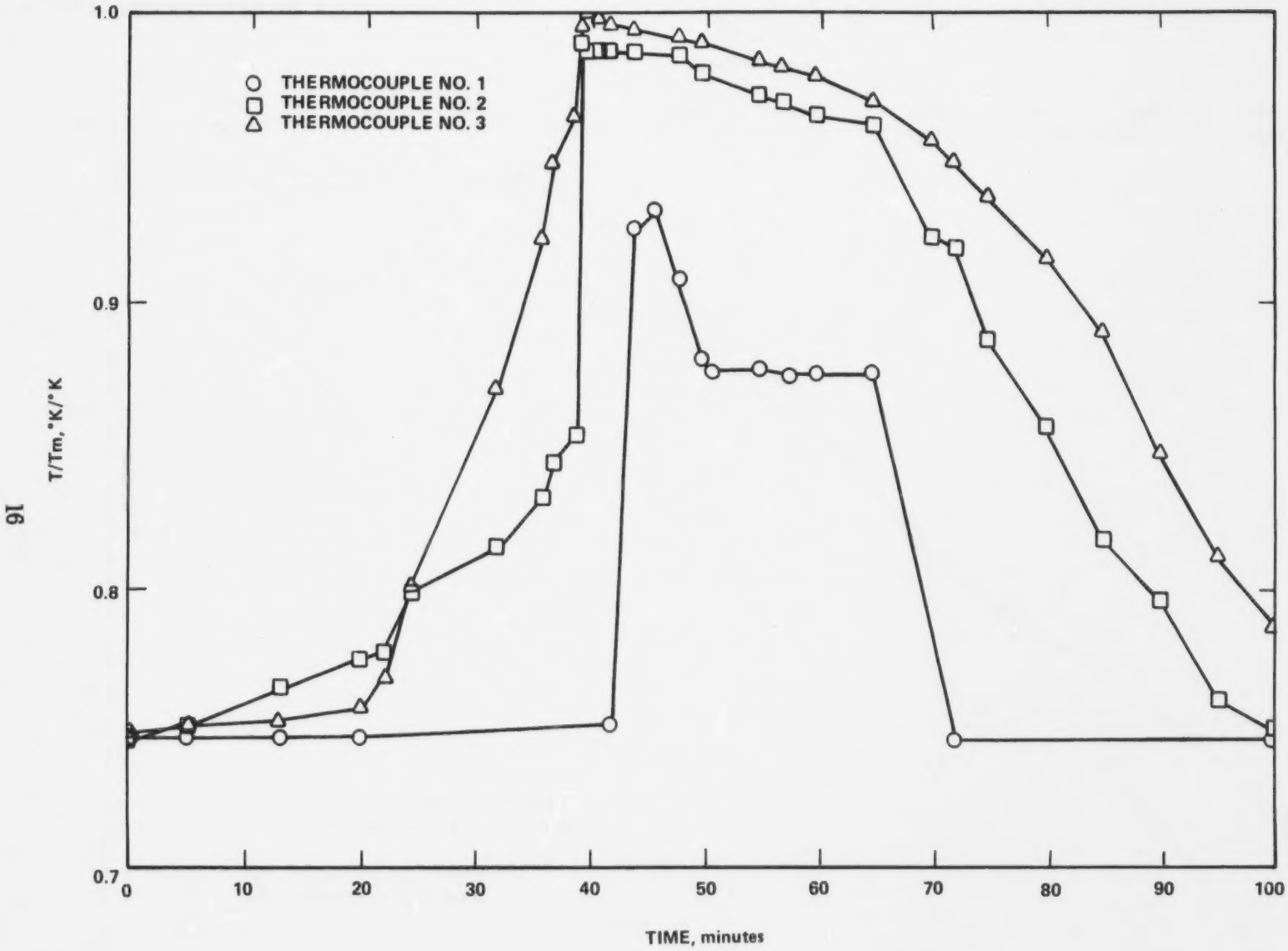


Figure 8. Temperature history of run No. 5.

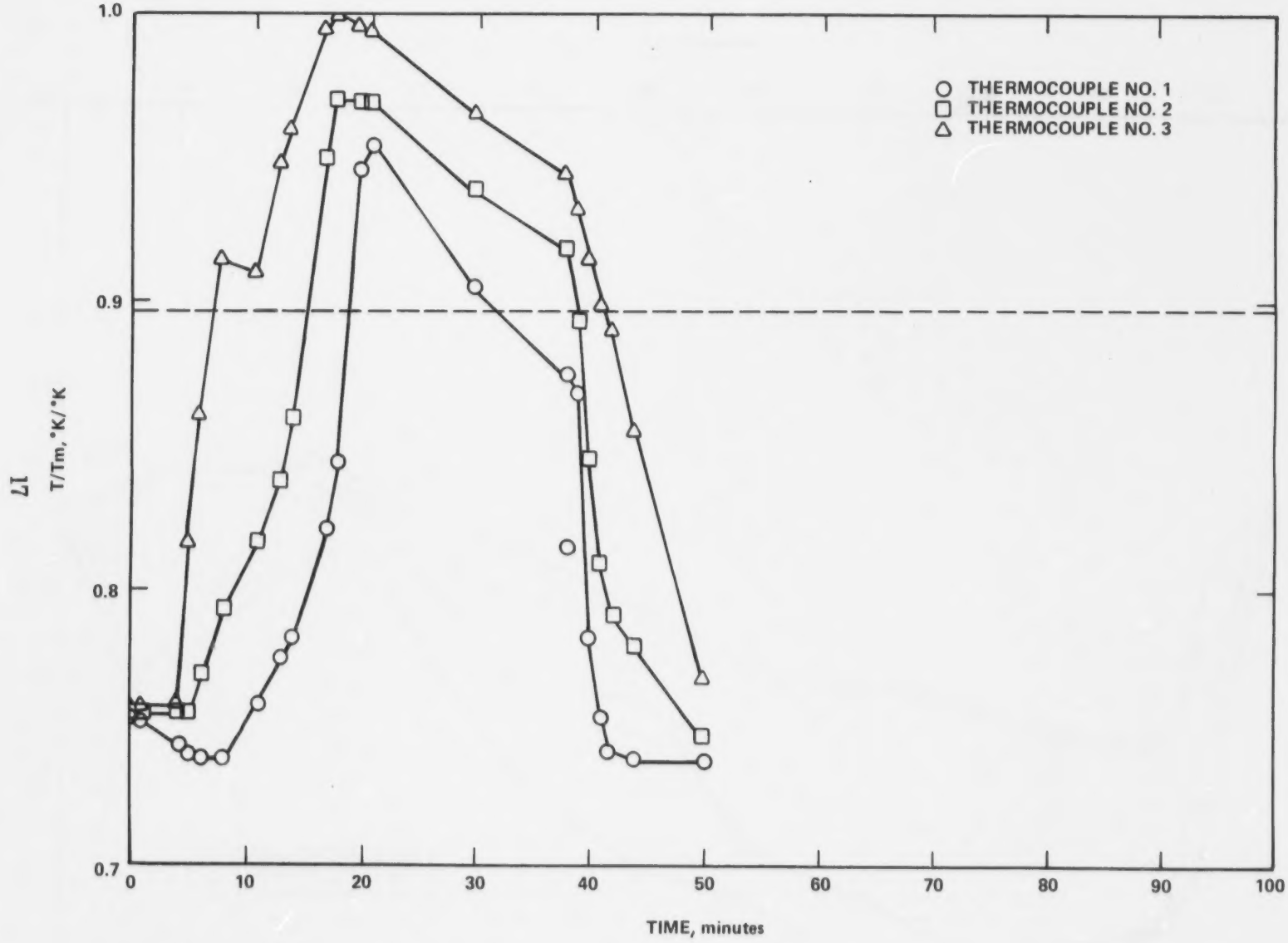


Figure 9. Temperature history of run No. 6.

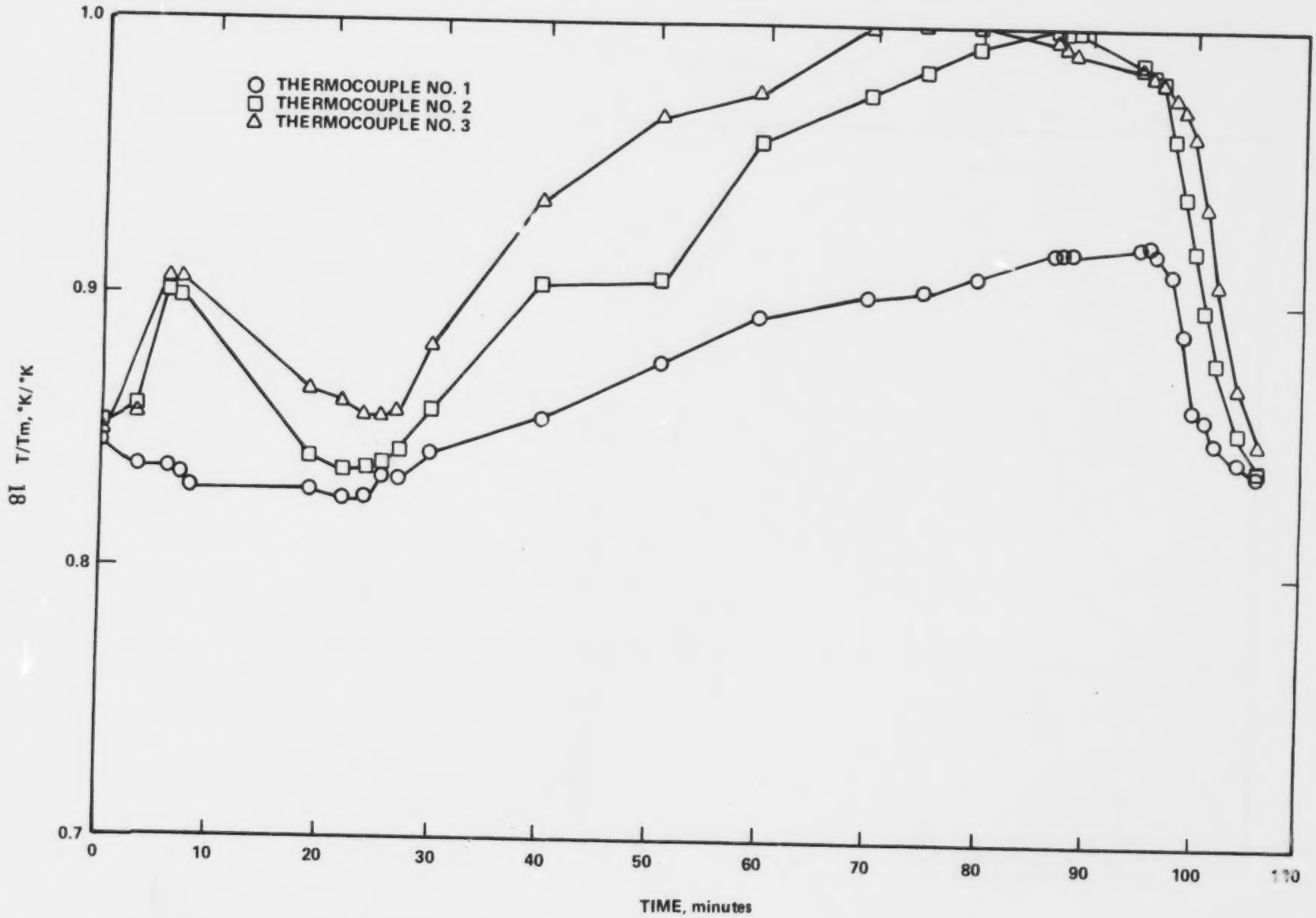


Figure 10. Temperature history of run No. 7.

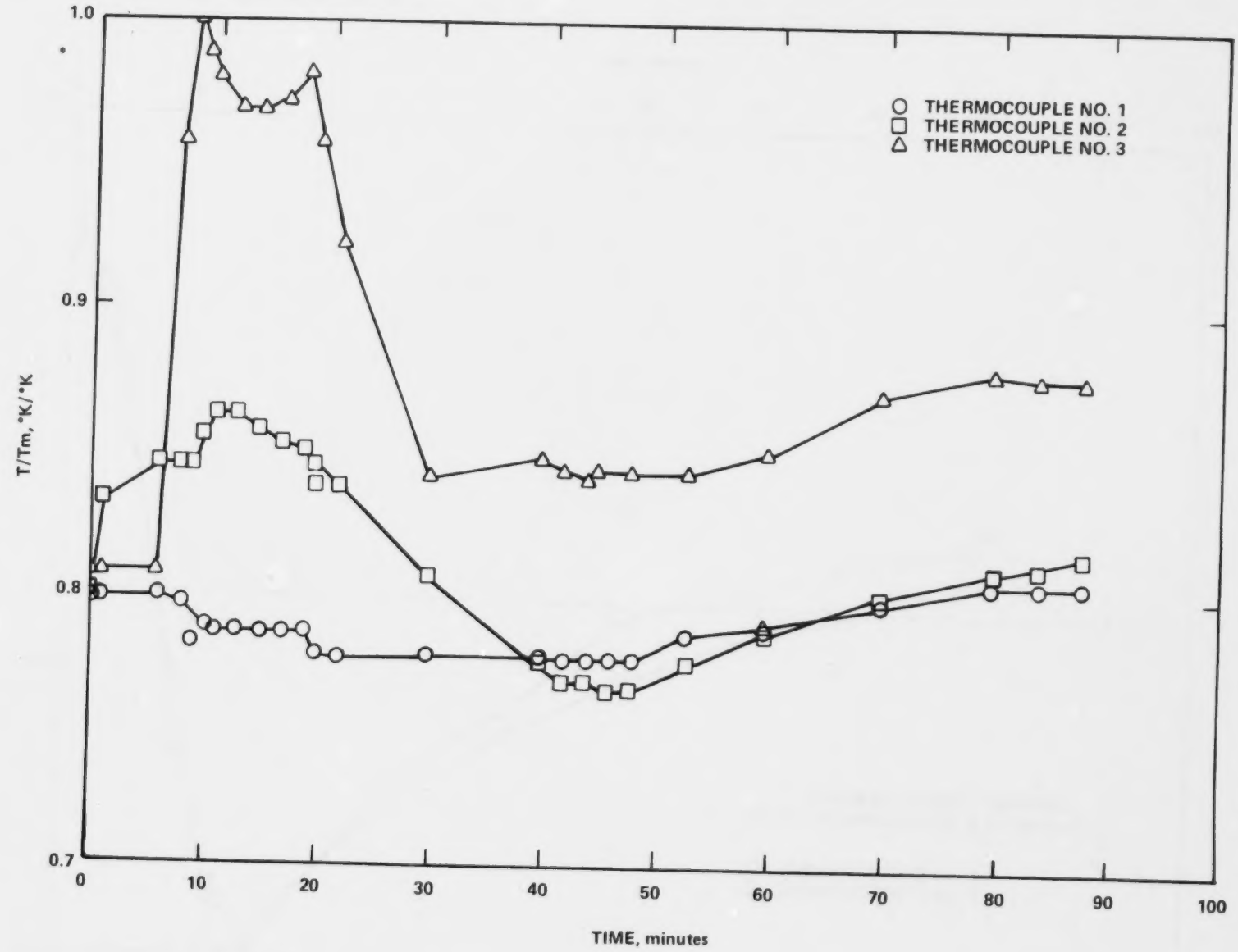


Figure 11. Temperature history of run No. 8.

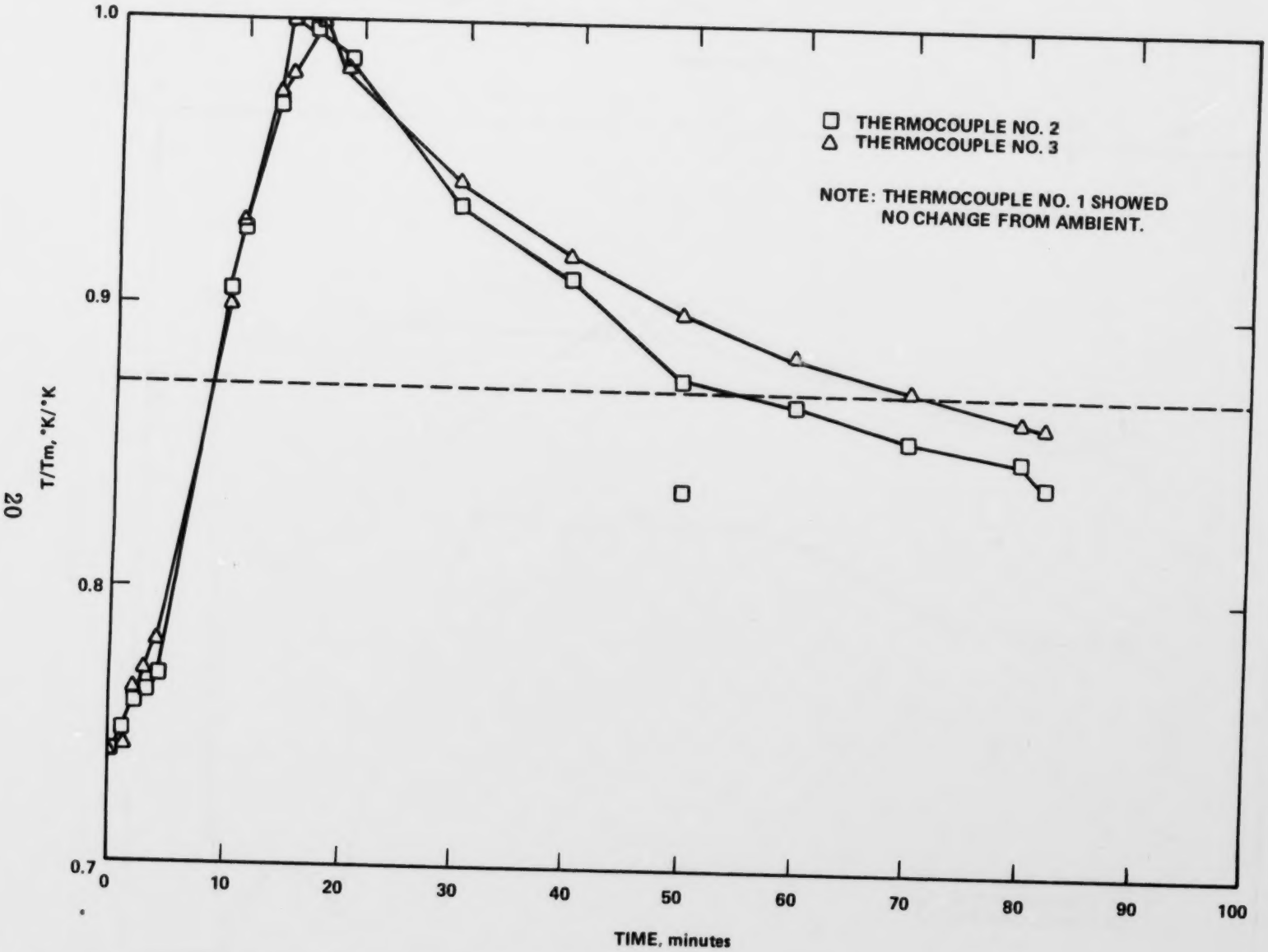


Figure 12. Temperature history of run No. 9.

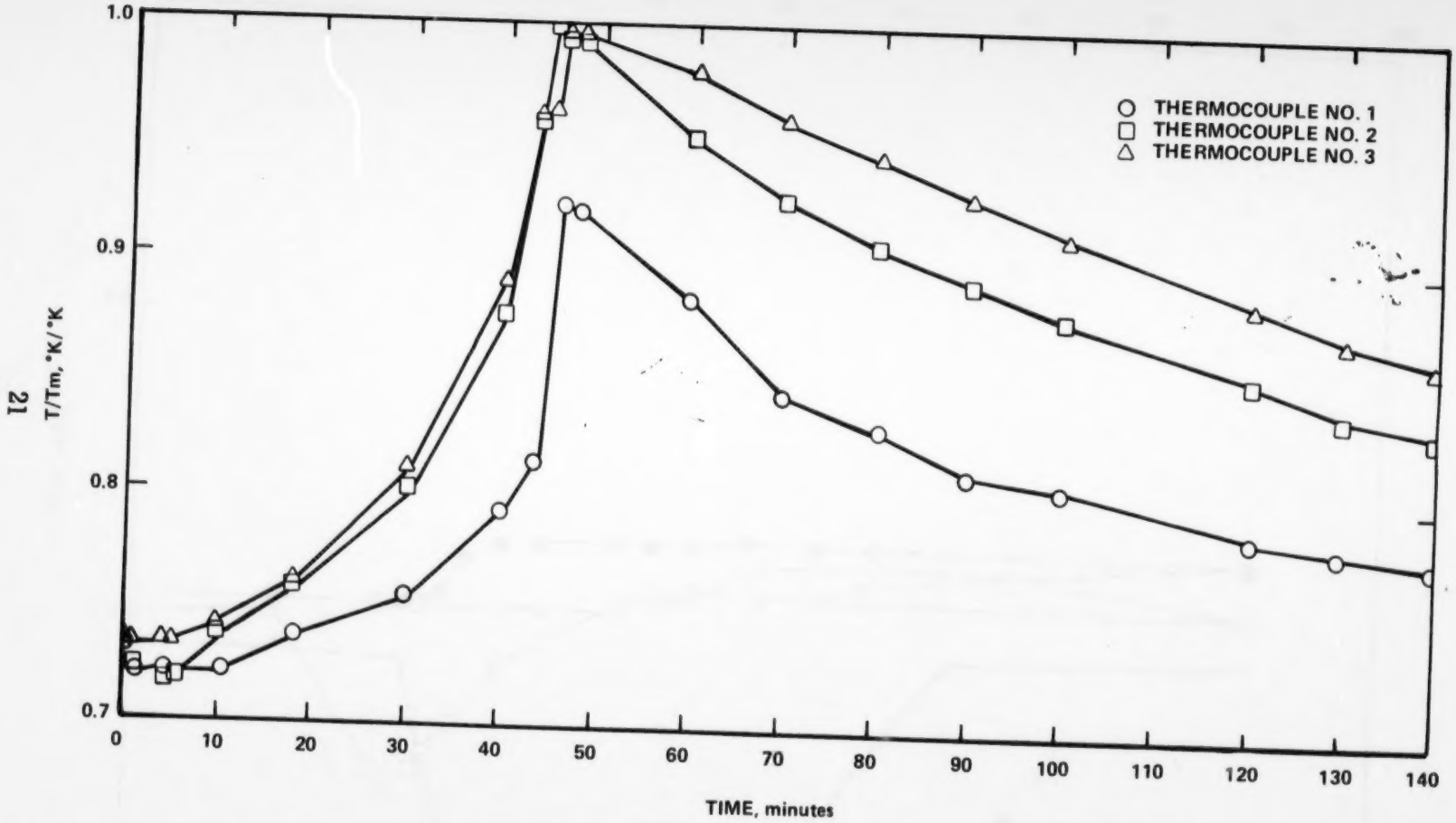


Figure 13. Temperature history of run No. 10.

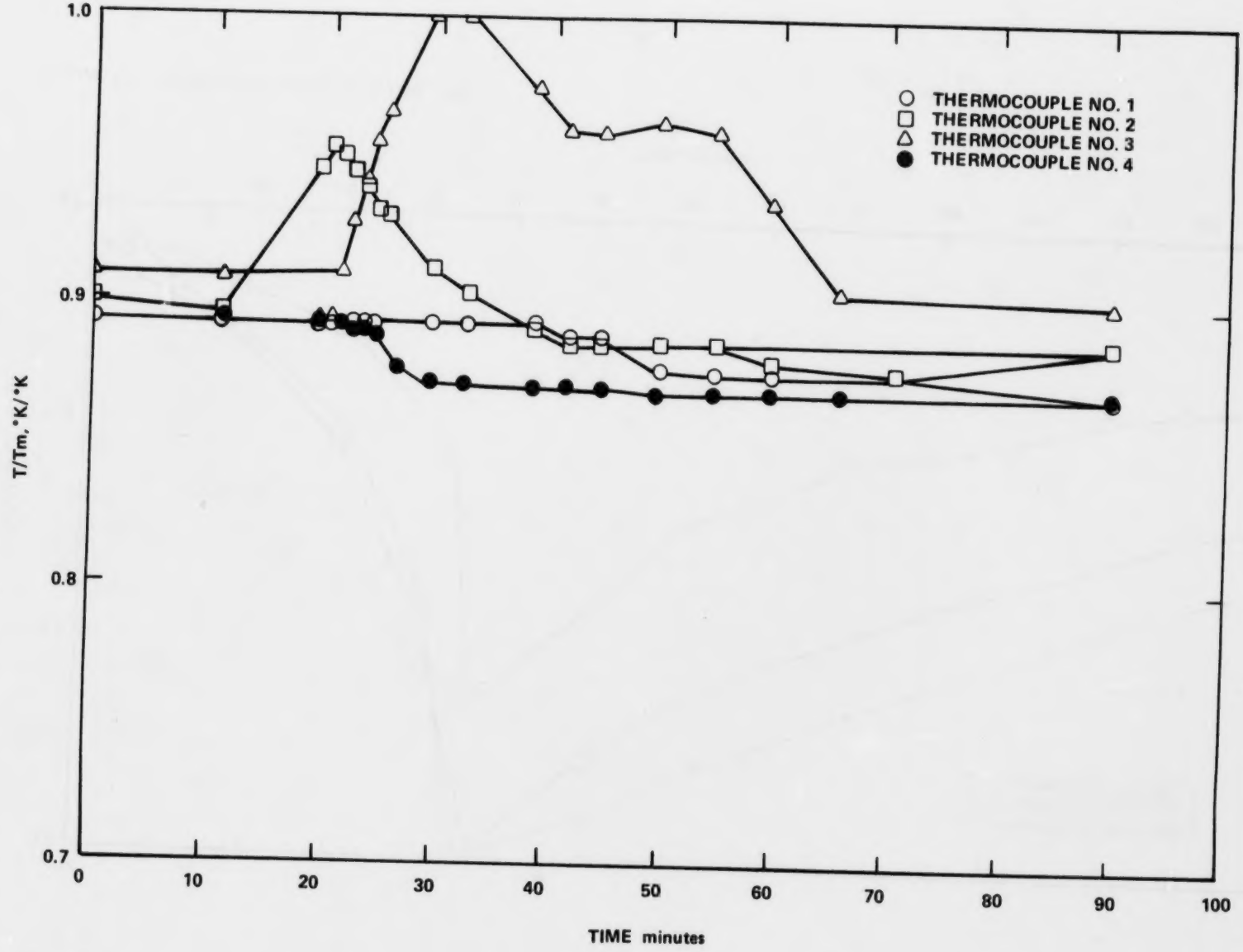


Figure 14. Temperature history of run No. 11 (in Plexiglas column).

Procedure

1. Place thermocouples at locations provided with adapters.

   Note: Thermocouple No. 1 is at the surface. Below it are thermocouples No. 2 and 3, respectively. Thermocouple No. 3 is 10.2 cm (4 in.) or 2.54 cm (1 in.) from the base of the square (Plexiglas) or cylindrical (steel) column, respectively.

2. Measure the volume of the fluidized-bed combustor residue (FBCR) with a beaker.

3. Fill the column with the FBCR and measure the height of the FBCR.

4. Keeping the water holder away from the column, turn on the water, switch on the peristaltic pump, and wait until water reaches the predetermined level adjusted by the drain tube of the water holder.

5. Measure the flow rate of the water holder (using a stopwatch and a graduated cylinder) and record the time at which reading was made.

6. Start the recorder at 1 cm/min. and swing the water holder to a position above the column, keeping water drops away from the edges of the column to avoid channeling.

7. Push the water holder set away from the column to stop the water supply after a predetermined duration.

   Note: Temperature histories at thermocouples No. 1, 2, and 3 are recorded automatically.

8. When the temperature at thermocouple No. 3 reaches 77°C (170°F), stop the recorders, measure the height change of the FBCR, and clean up the hydrated FBCR from the column.

9. Water can be re-supplied after the temperature gets to the plateau at the maximum to observe the rate of cooling as water is supplied.

10. Turn off water.

FBCR Samples

Three samples were tested. The first sample was obtained under non-steady state conditions of the Sampling and Analytical Test Rig: repeatability of the hydration processes was impossible to establish. The other two samples were obtained under steady state operation. Table 1 illustrates the combustor conditions for the various runs. Note that calcium/sulfur (Ca/S) ratios for the samples are 3 and 3.3 for the second and third samples, respectively.

Results and Discussion

Tables II-1 through II-11 are temperature histories of all experiments in tabular form. A typical run is also shown in Appendix II. The maximum temperature, T_m, and the time, t_m, at which T_m occurred at each thermocouple are listed in Table 2. Maximum temperatures are in the range of 22°-130°C (72°-266°F). It is seen from Table 2 that maximum temperature took place at

thermocouples 2 and 3 at almost the same time and somewhat later at thermocouple 1. The maximum temperature at thermocouple 1 is generally lower than those at thermocouples 2 and 3, since the initial contact of water with the FBCR is made at thermocouple 1; heat generated is taken away with water flow faster than heat at thermocouples 2 and 3. Table 3 lists, for each run, the volume of the FBCR, total volume of water, the volume ratio of FBCR to water, the maximum temperature, the time at which the maximum temperature occurs, water holding capacity, t_m duration, the percent volume change, and resupply of water or not. The reason for the resupply of water is to observe how fast cooling takes place in the FBCR after the temperatures at thermocouples 2 and 3 level off at T_m.

Table 1

FLUIDIZED BED COMBUSTOR/SATR CONDITIONS

	Sample I	Sample II
Coal type	Arkwright 1/4 x 50	Arkwright 1/4 x 50
Sorbent type	Greer limestone 8 x 20	Greer limestone 8 x 20
Air velocity, m/sec (ft/sec)	1.37 (4.5)	1.37 (4.5)
Bed temperature, °C (°F)	868 (1595)	871 (1600)
Excess Air, %	22	22
Ca/S ratio	3	3.3
Bed height, m (in.)	0.76 (30)	0.76 (30)
Bed area, m^2 ($in.^2$)	0.21 (325)	0.21 (325)
Total air flow m^3/min (scfm)	4.56 (161)	4.56 (161)
Coal feed rate, kg/hr (lb/hr)	21.79 (48)	28.6 (63)
Sorbent feed rate kg/hr (lb/hr)	6.81 (15)	9.08 (20)

Table 2

T_m AND t_m AT THREE POSITIONS

	Thermocouple Locations					
	1		2		3	
Run No.	T_m, °C (°F)	t_m, min.	T_m, °C (°F)	t_m, min.	T_m, °C (°F)	t_m, min.
1[a]	100 (212)	27	123 (254)	27	124 (256)	27
2[a]	100 (212)	33	119 (247)	28	122 (252)	33
3[a]	62 (143)	54	118 (245)	53	111 (231)	53
4[ab]	———	—	66 (151)	207	57 (135)	207
5[a]	96 (205)	45	119 (246)	40	124 (255)	40
6	99 (210)	21	105 (221)	18	117 (243)	18
7	48 (118)	95	74 (166)	87	76 (168)	75
8	22 (72)	0	46 (114)	11	98 (208)	9
9[b]	———	—	129 (264)	15	125 (257)	17
10[a]	99 (210)	46	130 (266)	45	129 (264)	46
11[a]	22 (72)	0	43 (109)	21	58 (137)	30

Notes: a) Using Sample I of Table 1; Sample II was used in the other four runs.

b) No change from ambient.

Figures 4-14 show temperature histories with normalization of the temperatures with respect to the maximum temperature for each run. All runs except the one covered by Figure 14 were made in the stainless steel column; the run of Figure 14 was made in the Plexiglas column. Observations from these Figures 4-14 and Tables 1-3 follow:

1. Controllability of temperature increase of the FBCR. A purpose of this experiment was to determine a technique to control temperature increase due to the lime hydration process as it contacts water. The control technique is to keep the temperature of the FBCR below 77°C (170°F), above which the lysimeter material, Plexiglas, will be deformed. Run No. 4 supplied 18,972 ml of water for a 63-minute period; this resulted in a maximum temperature of 66°C (151°F), occurring 207.3 minutes after the experiment was started. The experiments by Sun[7] confirm these results: the volume ratio of the FBCR to water is less than or equal to 1. Note that, regardless of mixing the FBCR and water, the temperature rise can probably be controlled if the ratio of the FBCR to water by volume is near or less than 1.

As the FBCR/water ratio increases beyond 1.2, heat generation in the hydration processes becomes spontaneous, with maximum temperatures reaching about 127°C (260°F), which is higher than the saturation temperature of 1 atmosphere. See Table 3. The maximum temperature at the surface of the FBCR is in the range of 48°-100°C (118°-212°F), except for runs No. 8 and No. 11 which did not get above ambient.

Table 3

THE MAXIMUM TEMPERATURE, FLOW RATE, TIME FOR t_m, ETC. FOR EACH RUN

Run No.	FBCR (ml)	Water (ml)	FBCR/Water (ml/ml)	T_m (°F)	t_m (min)	WHC[a]	t_m duration (min)	Volume change (%)	Resupply of water
1	2250	559.8	4.02	256	27	2.285	6	--	Provided
2	1800	197.1	9.12	252	33	2.285	3	61.2%	"
3	1800	182	9.89	245	52.8	2.285	14	48.2	Not provided
4	1800	18972	0.95	151	207.3	2.285	63	No change	"
5	2250	2754.2	0.818	255	40	2.285	47	--	
6	1800	254	7.086	243	18	2.3784	8	38.3	
7	1800	1500	1.2	168	75	2.3784	24		
8	1800	2608.5	0.69	208	9	2.3784	47	21.8	
9	1350	107.1	12.6	264	15	2.3784	3	--	
10	1800	219.2	8.21	266	45	2.285	4	33.9	
11	1750	3650.4	0.479	137	30	2.285	78	No change	

[a]Water holding capacity = weight of FBCR/weight of water.
Density of sample I = 1.160 gm/cm^3; Density of sample II = 1.287 gm/cm^3.

The FBCR at thermocouples 2 and 3 would maintain a temperature above 77°C (170°C) at least for more than an hour as it undergoes the hydration process, implying that the Plexiglas column would be deformed seriously toward the base of the column. Results of resupplying water after the temperature reaches the maximum temperature plateau are to accelerate cooling of the FBCR so that 1 hour period above 77°C (170°F) can be shortened to 20-30 minutes. (See Figures 4, 5, 9, and 11.) However, resupplying water after temperature reaches the maximum plateau is not a satisfactory control method for temperature increases.

Taking the monthly average rainfall of the West Virginia area,[9] the amount of water for controlling the temperature below 77°C (170°F) corresponds to a 4-month net flux for 1800 ml FBCR.* Therefore, changes in pH of runoff or leachates would be significant in the entire hydration process; pH in the initial stage of hydration would change drastically.

2. Heat generation. Figure 15 presents a normalized temperature history at thermocouple No. 1 based on all of the runs. Using the maximum temperature, T_m, from each run and the time, t_m, at which T_m occurred, temperatures and times are normalized and their dimensionless temperature histories are plotted. In a similar manner, Figures 16 and 17 are normalized to yield dimensionless temperature histories at thermocouples 2 and 3, respectively. Figures 15 and 16 indicate two distinctive types of temperature histories: one for experiments in which complete temperature control to 77°C (170°F) was possible; the other in which hydration takes place with an insufficient amount of water for temperature control. However, thermocouple No. 3

*See Appendix III

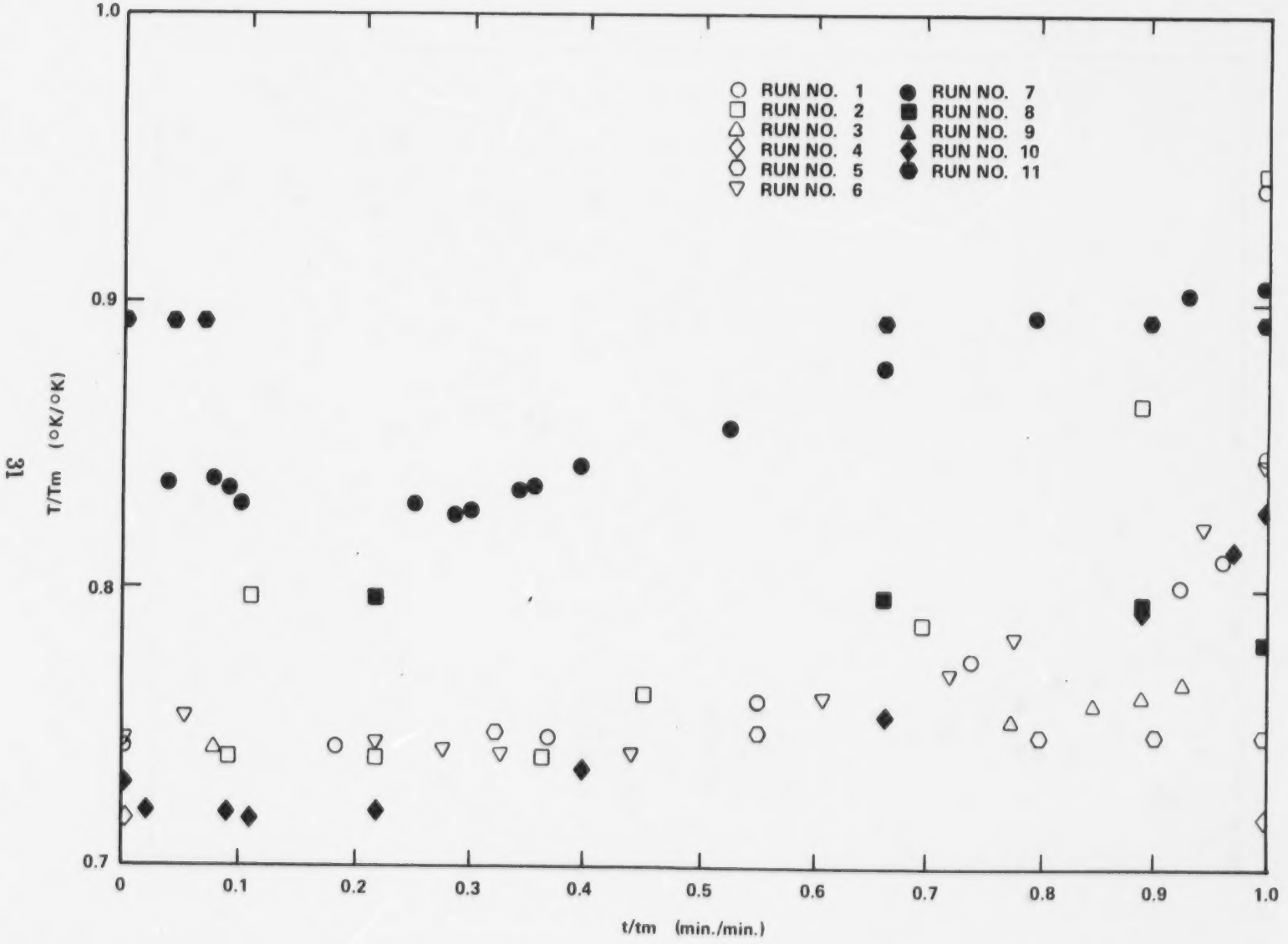


Figure 15. Dimensionless temperature history at the initial contact of water with FBCR.

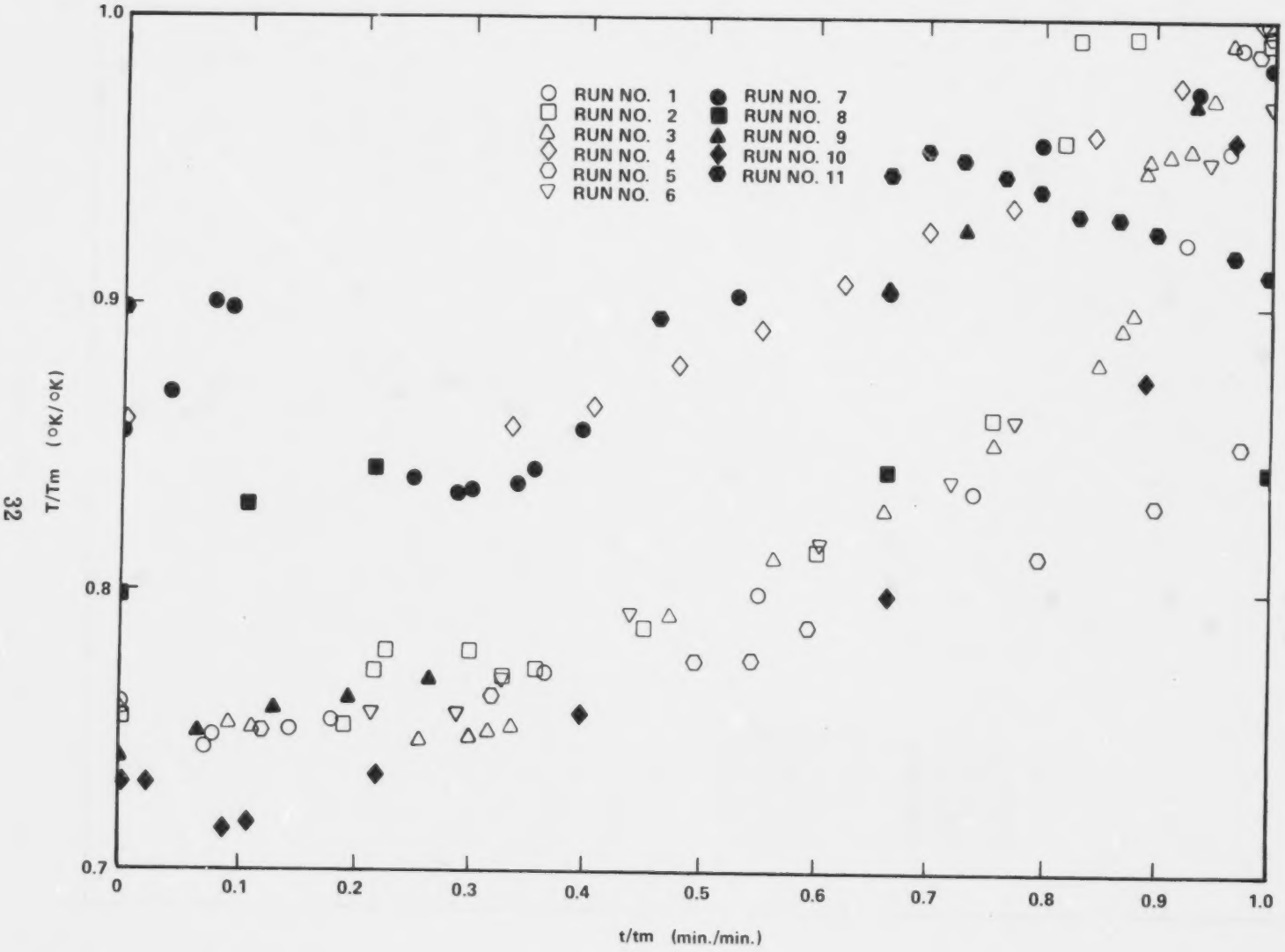


Figure 16. Dimensionless temperature history at thermocouple position 2.

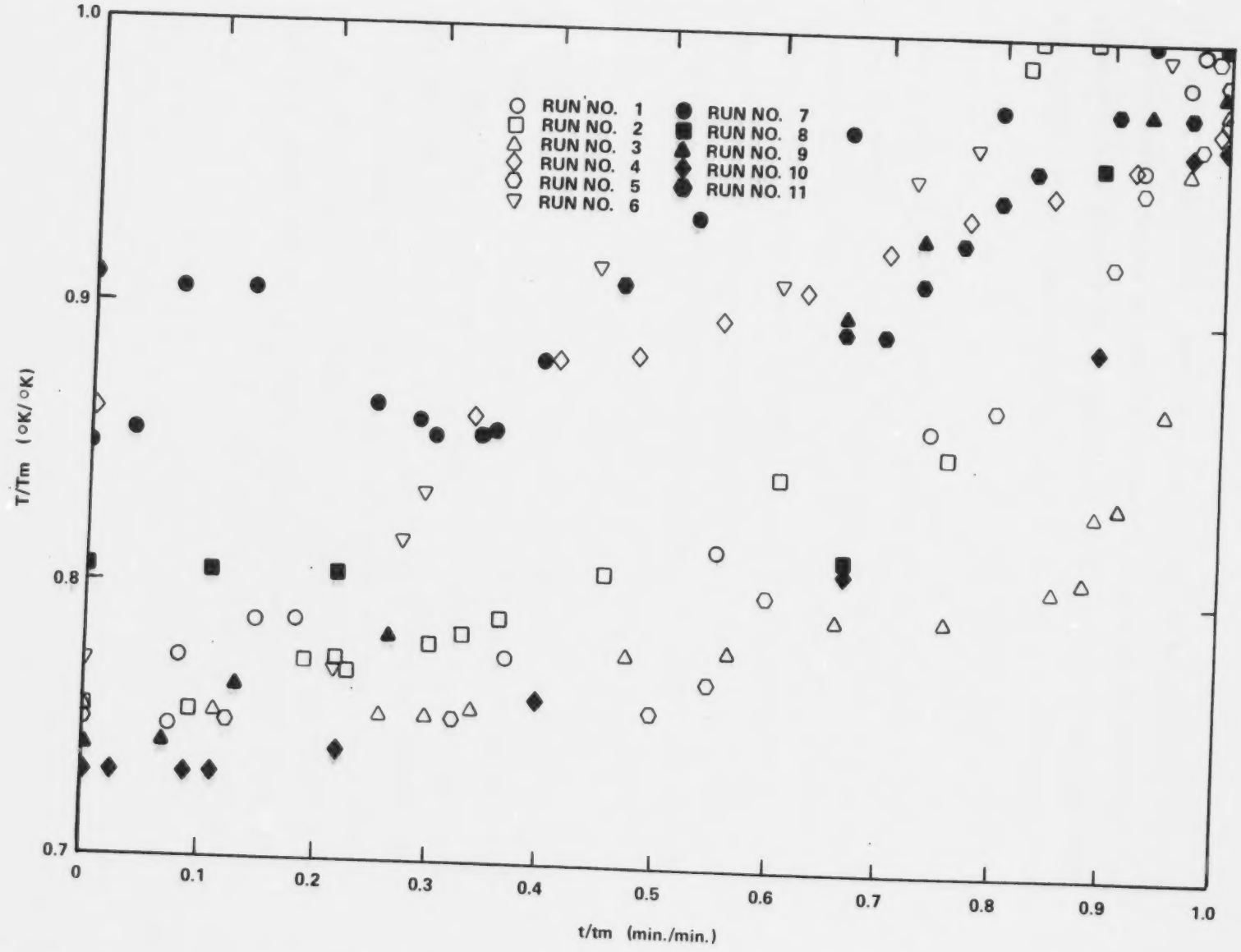


Figure 17. Dimensionless temperature history at thermocouple position 3.

gives no indication of the two types of histories. (See Figure 17.) The first type appears to be curve with a slower slope than the second, indicating that generated heat is quickly dissipated through the infiltrating water. However, in a deeper location, the rate of heat generation exceeds its dissipation rate, yielding a higher temperature.

Thermal gradients in the FBCR may cause water to move from warm to cool areas in both the liquid and vapor phases, and the rate of transfer may be greater than can be predicted with Fick's law and the diffusion coefficient for water vapor into air.[10] Several investigations have been published on two-phase heat and mass transfer from stationary sources.[11-13] However, no work has been reported on two-phase heat and mass transfer from a mobile heat source.

In this description of flow behavior, hydraulic diffusion is coupled with thermal diffusion. The device used does not seem to furnish proper data for transient hydraulic diffusion. Until the FBCR is fully saturated, the permeability coefficient of the FBCR cannot be obtained. Once the FBCR is fully saturated with water at a given temperature, the permeability coefficient can be observed.[8] This is a condition in which heat is not generated: heat is transferred at a steady state so that thermal gradients are fixed through the layer of the FBCR.

3. Changes in chemical characteristics. As the hydration process takes place, quicklime and calcium sulfate absorb water and become components which are chemically different from the original components. Test duration for heat generation was in the range of 2.5 to 3 hours. Mehta[14] reports that the hydration can be extended to 6 hours and that volume expansion occurs as in commercial cement. This suggests that the 2.5 to 3 hour test may not be long enough to observe the FBCR volume expansion.

The main concern of the experimental investigation was to find a temperature control technique. However, the FBCR volume expansion may crack the FBCR and eventually lead to channeling FBCR landfills. The channeling may cause leachate infiltration, accelerating ground water contamination. Further investigation of the volume expansion phenomenon is desirable.

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APPENDIX I

FLOW RATE HISTORIES

Flow rate histories and average flow rates for each run are shown in Figures I-1 through I-10, following.

For periods of testing, average flow rates are linear in most runs as shown by the arrows intersecting the "y" axes. Their averages are used to compute the total quantity of flow supplied to the FBCR.

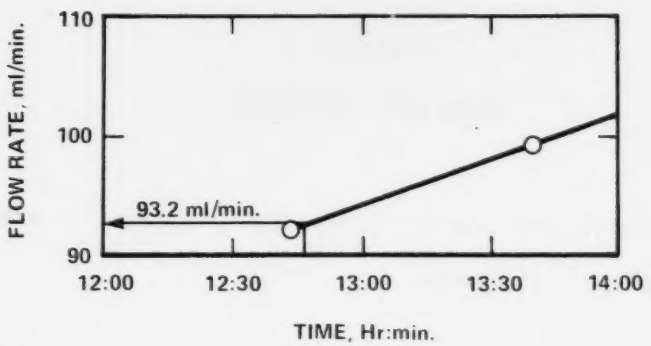


Figure I-1 Flow rate history and its average for run No. 1.

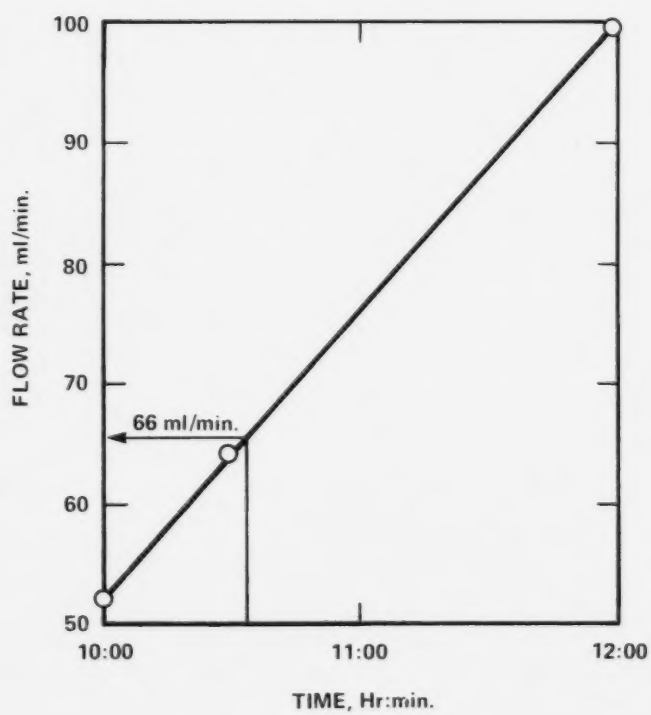


Figure I-2. Flow rate history and its average for run No. 2.

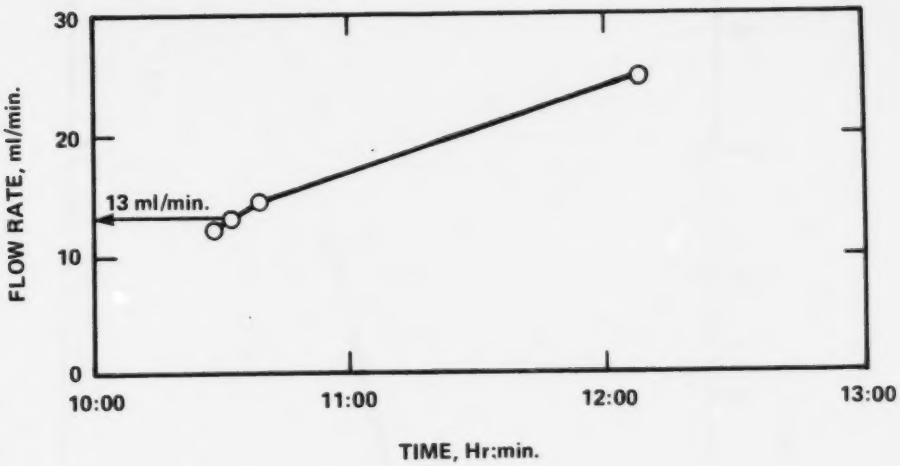


Figure I-3. Flow rate history and its average for run No. 3.

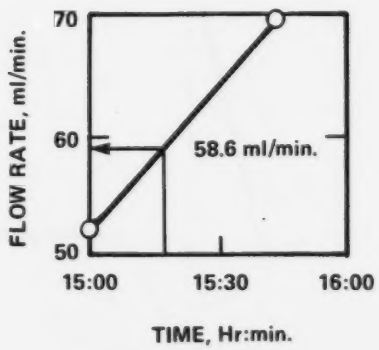


Figure I-4. Flow rate history and its average for run No. 5.

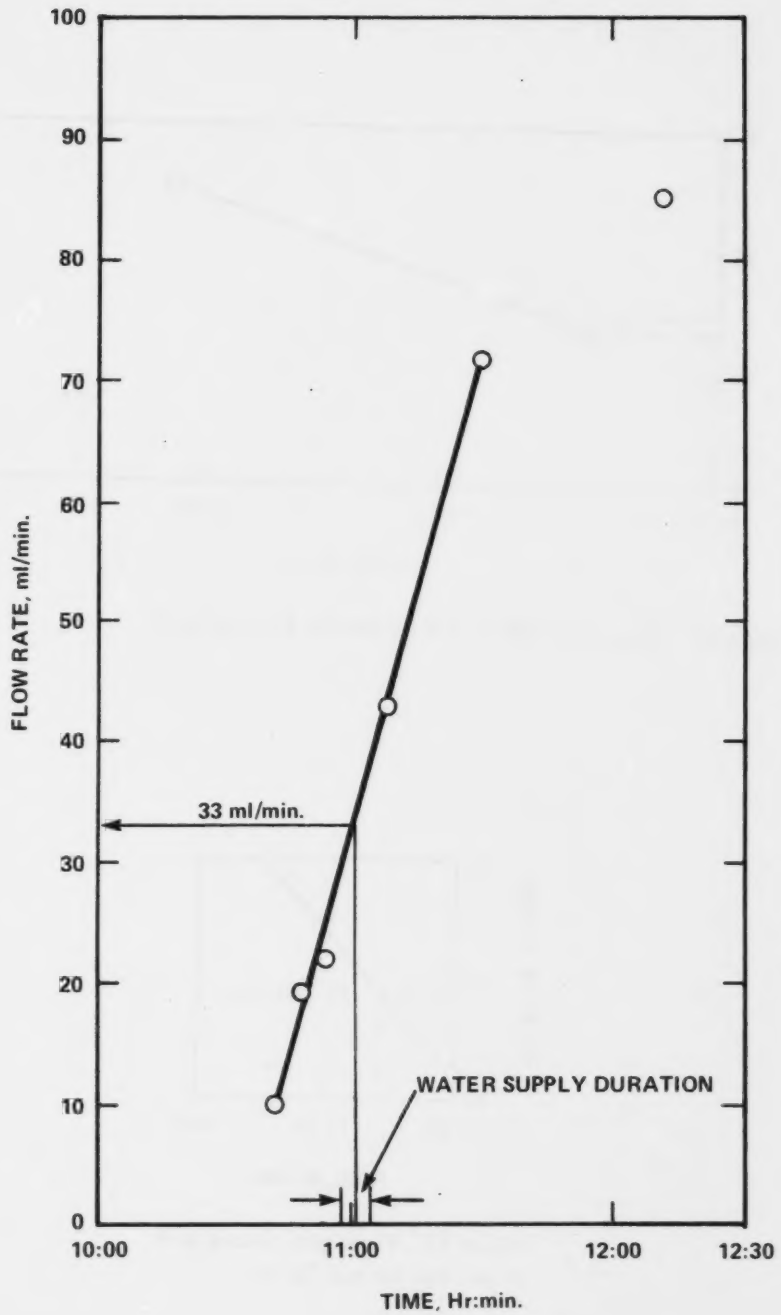


Figure I-5. Flow rate history and its average for run No. 6.

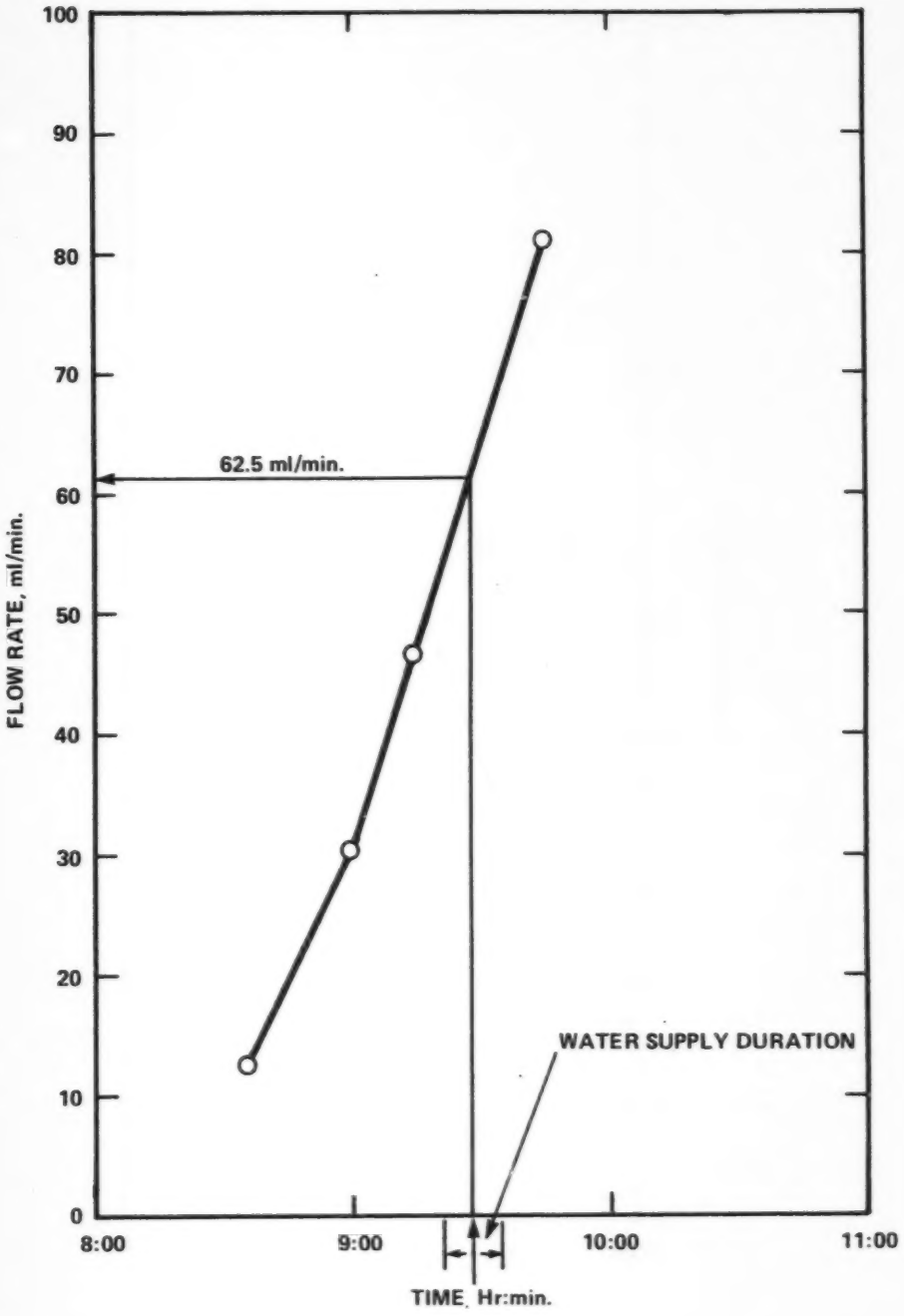


Figure I-6. Flow rate history and its average for run No. 7.

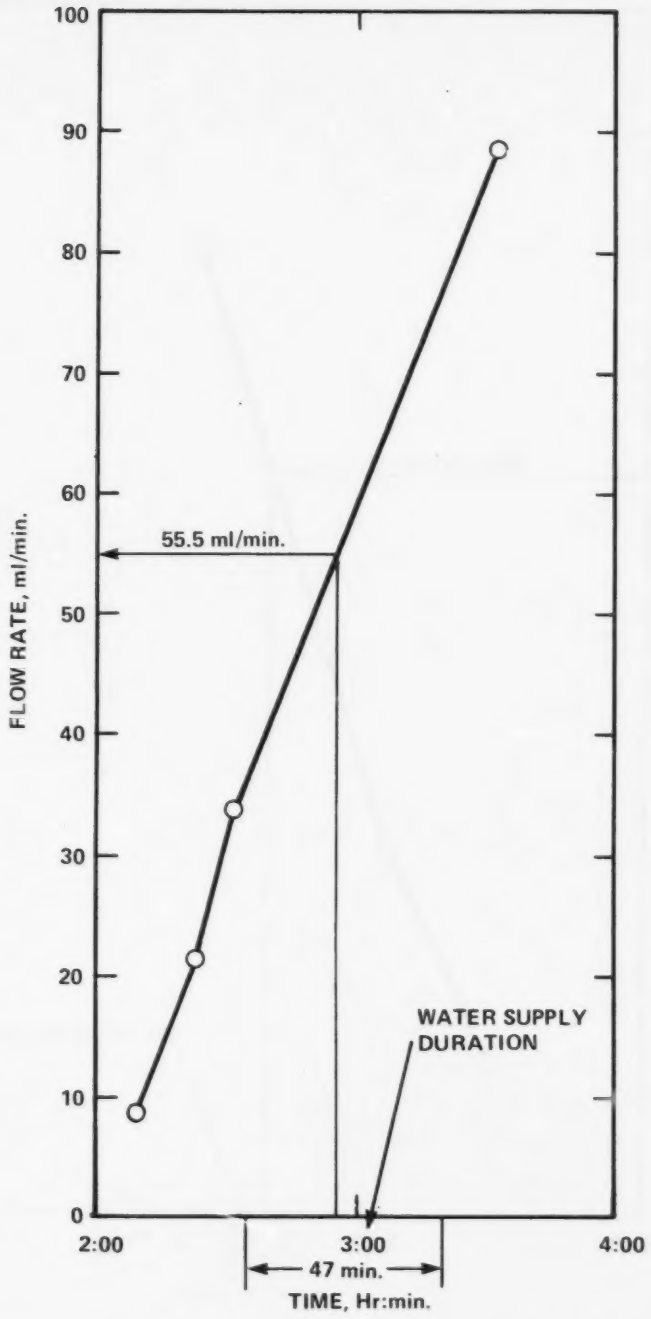


Figure I-7. Flow rate history and its average for run No. 8.

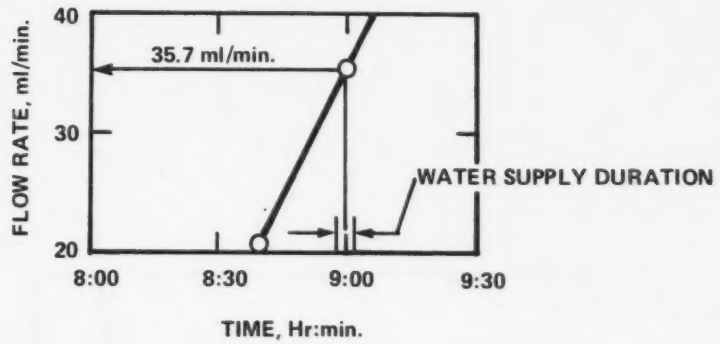


Figure I-8. Flow rate history and its average for run No. 9.

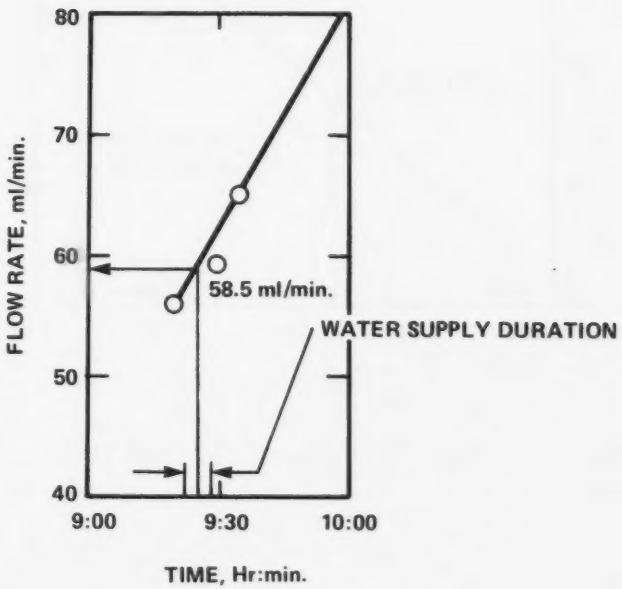


Figure I-9. Flow rate history and its average for run No. 10.

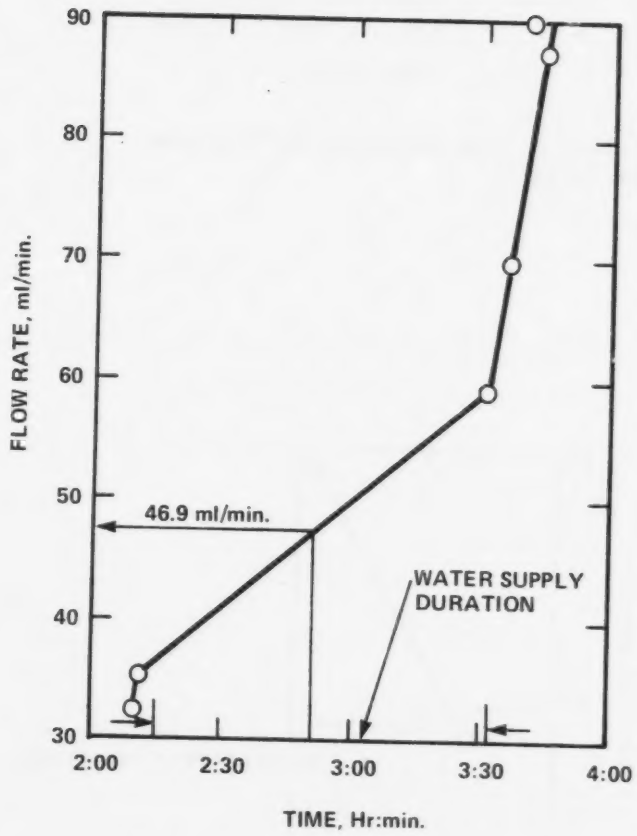


Figure I-10. Flow rate history and its average for run No. 11.

APPENDIX II

RUN DATA AND TYPICAL RECORDER RESULTS

Tables II-1 through II-11, following, are temperature histories for all runs.

Figure II-1, following, represents a recording from an Angus Recorder, at a chart speed of 0.5 in./min (1.27 cm/min.). The temperature scale appears on the graph. The temperature history is for thermocouple No. 1 (at the surface).

Figure II-2, following, shows temperature histories for thermocouples No. 2 (heavier line) and 3 in the FBCR. The reference for the trace for thermocouple No. 2 is the base of the graph. That for No. 3 is 1 in. (2.54 cm) above the base. At a chart speed of 1 cm/min, 1 in. (2.54 cm) represents 1 mv.

TABLE II-1. TEMPERATURE HISTORY FOR RUN NO. 1

Time (min.)	Thermocouple No. 1	Thermocouple No. 2	Thermocouple No. 3
0	74	75	77
2		75	77
2.2		77	95
4		80	104
5	74	82	104
10	75	94	101
15	85	113	125
20	95	139	156
25	113	200	223
26	120	223	245
26.3		249	254
27	212	252	256
28		254	255
29		252	254
30	212	252	253
31	210	252	253
32	205	252	253
33	190	249	252
34	175	244	247
40	100	219	237
42	88	146	201
52	77	139	193
55		127	182
60		125	176
65		119	166
70		114	157

TABLE II-2. TEMPERATURE HISTORY FOR RUN NO. 2

Time (min.)	Thermocouple No. 1	Thermocouple No. 2	Thermocouple No. 3
0	72	73	77
3	67	73	77
6.4		73	89
7		87	91
7.7		91	88
10		91	95
11		85	98
12		87	102
15	83	97	114
20		116	139
23	100		
25		149	146
28		221	245
28.4		247	250
29		247	251
29.3	155		
30.5	212		
33		247	252
34.3	211		
37	210	238	248
38		232	243
39		204	234
40		148	222
41		121	199
42	70	108	195
43		102	186
44	63	99	178
45	63	91	157
46	63	82	135
50	63	58	73

Table II-3. TEMPERATURE HISTORY FOR RUN NO. 3

Time (min.)	Thermocouple No. 1	Thermocouple No. 2	Thermocouple No. 3
0	71	73	73
4	71	73	73
5	71	72	73
6	71	71	72
13		68	72
16		69	72
17		70	73
18		71	74
25		99	85
30		112	89
35		124	98
40	71	140	99
41	71		
45	75	160	108
46		169	110
46.4		173	113
46.8		208	125
47	77	209	126
48		211	129
50		225	152
51	115	239	211
52	135	244	227
52.8		245	231
53	140	245	231
54	143	242	229
55	142	240	227
56		236	225
57	136	232	214
58	133	230	211
59	125	225	205
60	120	222	202
61	118	217	197
66		205	179
71		192	161
75	83	183	148
80		174	137
83	71	166	130
90	71	140	115
95	71	138	107
100	71	131	104

Table II-4. TEMPERATURE HISTORY FOR RUN NO. 4

Time (min.)	Thermocouple No. 1	No. 2	No. 3
0	64	64	66
70		64	63
85		68	73
100		77	80
115		85	88
130		95	95
145		106	104
160		111	112
175		126	117
190		137	124
205		150	132
207.3		151	135
210		151	133

Table II-5. TEMPERATURE HISTORY FOR RUN NO. 5

Time (min.)	Thermocouple No. 1	No. 2	No. 3
0	74	76	76
5	74	77	77
13	74	87	79
20	74	94	82
22	74	96	90
24	74	104	112
32	74	121	160
36	74	134	197
37	74	143	217
39	74	169	228
39.5	74	246	251
40	74	245	255
42	78	245	253
44	200	245	250
45	205		
47	195		
48	185	242	248
50	167	239	247
51	165		
55	165	234	242
57	165	231	240
57.6	164	231	240
60		229	238
65		226	231
67	98		
70		198	222
72	73	188	216
85		123	174
90	73	98	145
95	73	83	119
100	73	74	101

Table II-6. TEMPERATURE HISTORY FOR RUN NO. 6

Time (min.)	Thermocouple No. 1	No. 2	No. 3
0	72	73	73
1	70	73	73
4	65	73	75
5	63	73	114
5.3	63	73	126
6	62	82	145
8	62	97	183
11	75	114	180
13	81	130	206
14	90	145	214
17	117	208	238
18	133	221	243
20	205	221	240
21	210	221	238
30	175	199	218
36	168	188	208
37	158	185	203
38	155	185	203
38.4		185	202
39	150	167	195
40	90	134	182
41	72	108	171
42	63	96	165
44	60	88	140
47	60	73	108
50	60	62	80

Table II-7. TEMPERATURE HISTORY FOR RUN NO. 7

Time (min.)	Thermocouple No. 1	No. 2	No. 3
0	75	75	73
3	70	85	77
6	65	105	108
7	63	104	108
8	60	104	108
19	60	67	83
22	58	64	79
24	58	65	77
26	63	67	77
27	63	69	78
30	68	78	93
40	77	107	126
51	90	109	145
60	100	141	159
70	105	153	167
75	107	158	168
80	110	163	168
81	110	166	165
88	116	166	163
89	116	166	162
95	118	160	158
96	118	158	157
97	116	156	156
98	105	143	152
99	92	129	149
100	80	117	142
106	65	66	72

Table II-8. TEMPERATURE HISTORY FOR RUN NO. 8

Time (min.)	Thermocouple No. 1	No. 2	No. 3
0	72	74	77
1	72	94	77
2	72	103	77
6	70	103	82
8	68	103	179
9	68	103	208
10	65	110	199
11	62	114	193
13	62	114	187
15	62	111	186
17	62	106	189
19	62	106	194
20	58	102	179
22	58	997	154
30	58	76	99
40	58	55	71
42	58	52	67
44	58	52	66
46	58	50	67
48	58	50	67
53	63	56	68
60	65	64	78
70	70	73	85
80	75	78	88
84	75	80	90
88	75	82	90

Table II-9. TEMPERATURE HISTORY FOR RUN NO. 9

Time (min.)	Thermocouple No. 1	No. 2	No. 3
0		77	77
1		84	79
2		90	93
3		93	99
4		97	106
10		195	201
11		211	212
14		241	245
15		264	250
17		263	257
20		254	251
30		217	222
40		198	205
50		174	190
60		167	179
70		157	171
80		154	163
82		147	162

Table II-10. TEMPERATURE HISTORY FOR RUN NO. 10

Time (min.)	Thermocouple No. 1	No. 2	No. 3
0	72	73	73
1	65	66	73
4	65	61	73
5	62	63	73
10	65	75	79
18	75	91	93
30	88	121	127
40	115	175	186
43.5	130	235	238
45	140	266	240
46	210	262	264
48	208	261	264
60	174	231	252
70	152	213	238
80	141	198	226
90	128	186	214
100	124	176	202
120	110	158	181
130	106	149	172
140	103	143	164

Table II-11. TEMPERATURE HISTORY FOR RUN NO. 11

Time (min.)	Thermocouple No. 1	No. 2	No. 3	No. 4
0	72	72	76	82
14	72	72	74	82
20	72	72	104	73
21	72	72	109	73
22	72	72	108	83
24	71	72	101	103
25	65	72	96	113
26	65	72	95	117
27	63	77	93	122
29	61	72	88	134
30	60	72	84	137
31	60	72	84	134
33	60	72	79	137
39	59	72	71	121
40	59	71	71	119
42	59	70	68	113
45	59	69	68	112
50	58	63	68	115
55	58	62	68	112
60	58	62	64	98
66	58	62	62	79
71	58	62	62	73
78	58	60	64	78
88	58	58	69	77

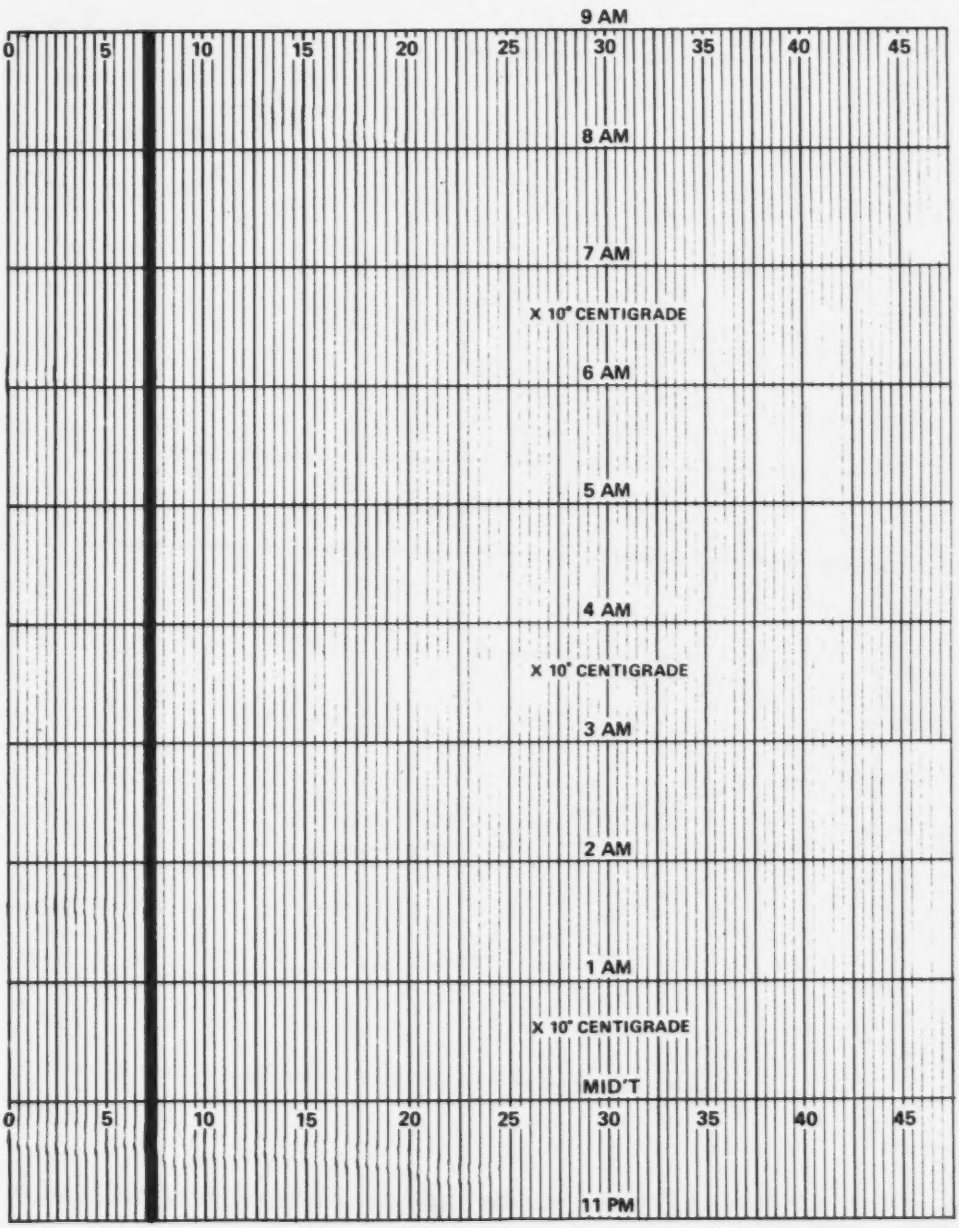


Figure II-1. A typical result from a recorder at the initial contact of water for FBCR (Thermocouple No. 1).

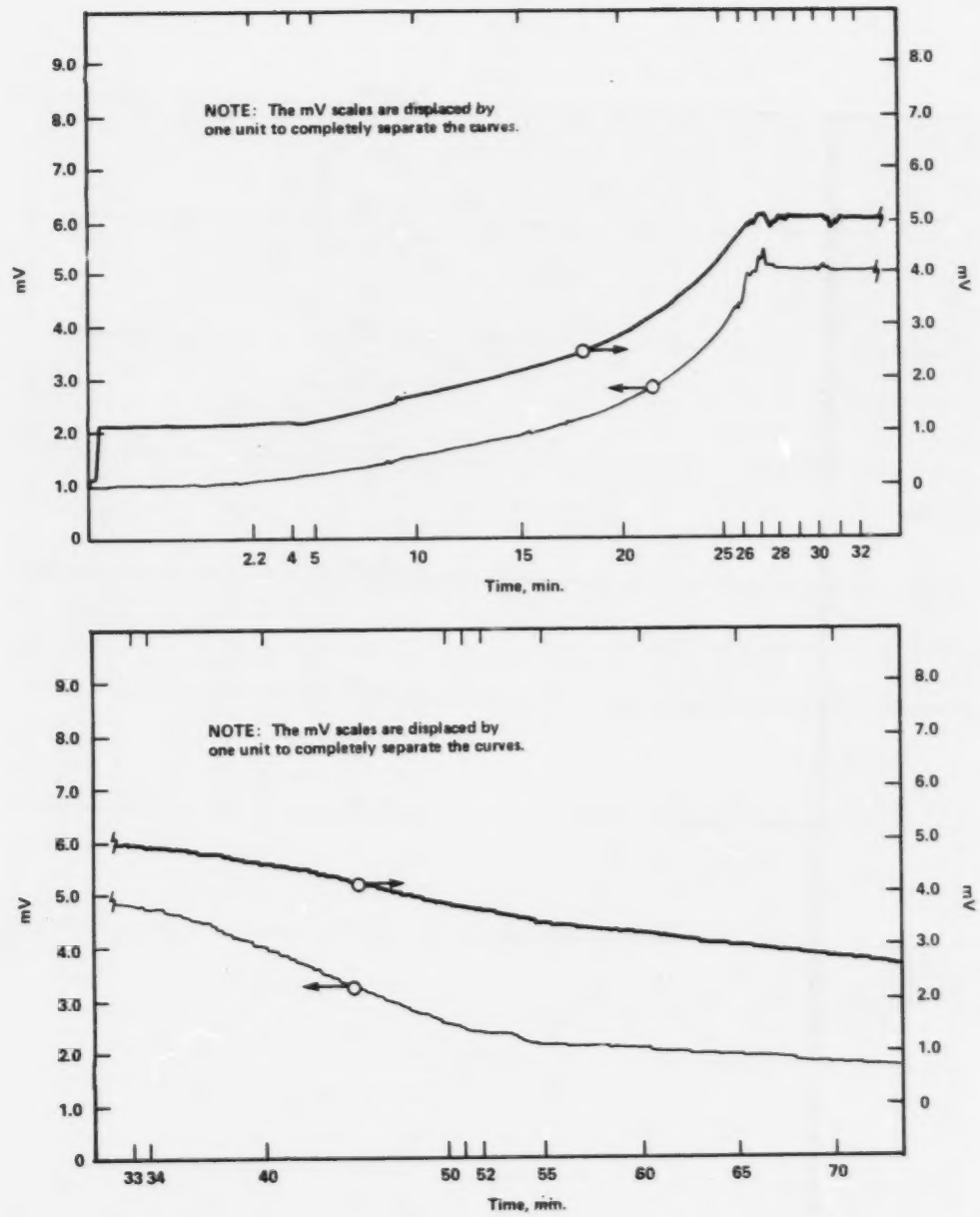


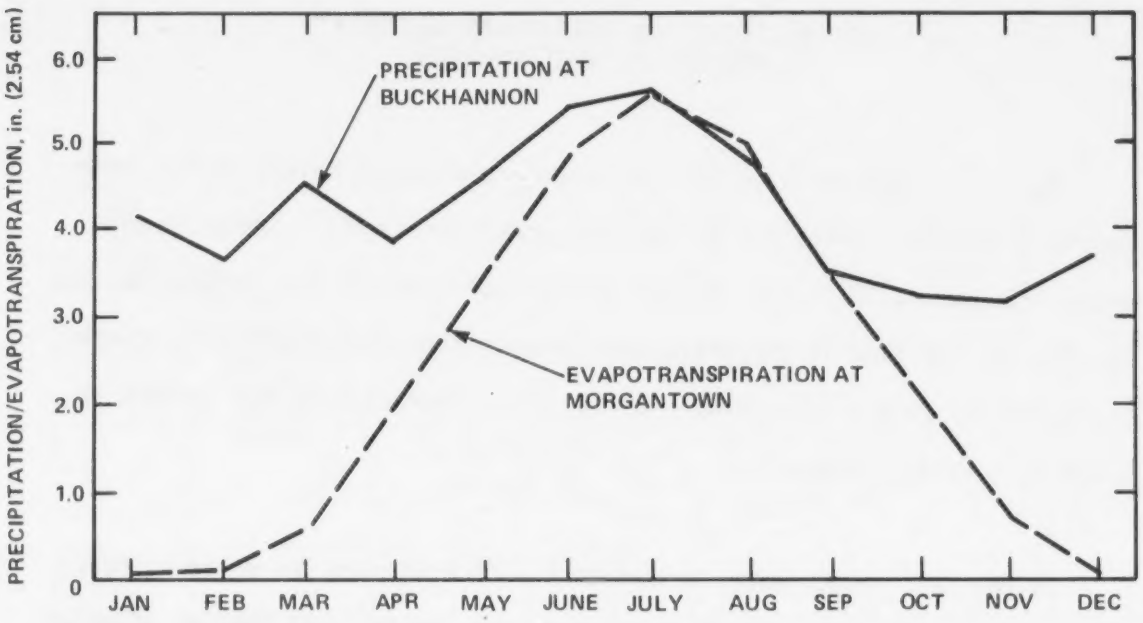
Figure 11-2. A typical result from a recorder at thermocouple positions No. 2 (bottom curve) and No. 3 (top curve).

APPENDIX III

PRECIPITATION AND EVAPOTRANSPIRATION AT MORGANTOWN, WEST VIRGINIA

The curves and table on the next page are based on Reference 9. Computation of evapotranspiration is based on monthly rainfall. Annual evapotranspiration was 18.01 in. Annual precipitation was 40 in. Neglecting the runoff, the net flux is the difference between the precipitation and evapotranspiration (e.g., 40 - 18.01 = 21.99 in.). Average flux for a month is 21.99/12 = 1.832 in./month.

In the test stand, water passes to the FBCR through the water holder. The area of the 16 holes in the water holder is 16 in^2. If 1500 ml of water passes through the 16 holes, the test is the equivalent of 14.54 cm of rain, falling in an average of 3.12 months. Therefore, 1500 ml of water (corresponding to a net flux of about 4 months) is needed to control temperature rise for 1800 ml of FBCR below 170°F.



Month	Precipitation[a]	Evapotranspiration	Net Flux
JAN	3.7 in.	0.01 in.	3.69 in.
FEB	3.17	0.06	3.11
MAR	3.96	0.61	3.35
APR	3.30	1.93	1.37
MAY	3.96	3.49	0.47
JUNE	4.75	4.84	0.00[b]
JULY	4.93	5.52	0.00[b]
AUG	4.22	4.93	0.00[b]
SEPT	2.99	3.46	0.00[b]
OCT	2.82	2.06	0.76
NOV	2.73	0.68	2.05
DEC	3.26	0.05	3.21
		TOTAL	18.01 in.

[a]Adjusted precipitation at Morgantown = $\left(\frac{44}{55}\right)$ x Precipitation at Buckhannon

[b]If (precipitation - evapotranspiration) < 0, net flux = 0.00

APPENDIX IV

MEMORANDUM: TEMPERAURE RISE RATE MEASUREMENT

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
RESEARCH TRIANGLE PARK
NORTH CAROLINA 27711

DATE: April 19, 1978

UBJECT: Measurement of Rates of Temperature Rises

FROM: Rhyn H. Kim
Advanced Process Branch
Energy Assessment & Control Div.

TO: P. P. Turner
Chief, Advanced Process Branch

A procurement request to purchase a two-channel strip chart recorder, etc. (see memorandum dated April 14, 1978) has been forwarded to the Procurement Branch. Further details of the measurement of rates of temperature rises are attached to this memorandum.

Any comments, recommendations, and corrections are welcome.

Attachment

cc: (w/attachment)
R. P. Hangebrauck
D. B. Henschel
W. B. Steen

Measurements of Rates of Temperature Rise

Objective: The purpose of the measurements is twofold. The first is to observe the maximum temperature and the rates of the rises in temperature of the Fluidized Bed Combustion/Sampling and Analytic Test Rig Residues when water is added to the residues. The second is to find a way of controlling the rates of the temperature rises, i.e., the rates of hydration of the high lime in the residues.

Apparatus: 6" x 6" x 1' Plexiglas column with five probe locations for thermocouples and pressure taps along the height of the side wall of the column (see sketch), a strip chart recorder, four thermocouples (ISA Type K), a peristaltic pump, a thermometer, several kinds of tubing and fittings and a vacuum pump.

Procedure: The procedure described below may be changed after some experiments, but it is envisioned to follow the procedure illustrated below.

1. Place coarse sand of 1/2" thickness at the bottom of the column, the FBC/SATR residues of 9-1/2", then coarse sand of 1/2" thickness on the top of the column. Obtain the solid samples from the bottom residues of SATR. The dry weight of the residues is to be measured before placing the residues in the column. Also determine the water holding capacity. The compaction of the residues is a loosened compaction, placing from the edges toward the center and keeping the thermocouple junction at the center of the cross-section of the column as it is filled with the residues.

2. The first four probe locations from the top are to be used for thermocouples.

3. Distilled water will be poured in the coarse sand layer to a height of 1/4" water initially.

4. Observe the maximum temperature from the recorder. Depending upon the maximum temperature, either a falling head method with increased water height or a sprinkle device will be used. The maximum temperature on which one method depends is the temperature at which Plexiglas is deformed (160°F). The sprinkle device may be a perforated spiral tubing connected to a pump. The pump will have a capability to control flow rates.

5. If the observed maximum temperature is below the temperature of deformation, add 1/4" water to the coarse sand layer until water infiltrates through the residue thickness.

6. Measure the permeability of the residue in that condition.

7. When water is infiltrating, observe the movement of heat generation with proper thermocouples.

8. Check if flow is channeling.

9. Repeat steps 5 through 8 with increased water height.

10. If the observed maximum temperature is above the temperature of deformation, the perforated spiral tubing should be used to sprinkle water from the top of the column at a calibrated flow rate. Go through steps 7, 8, 9, with different flow rates.

11. Mix the bottom residues with flyash in a production ratio of SATR and repeat the above procedures.

12. The conditions of the FBC/SATR, solid feed rates and other operating parameters should be representative of usual AFBC conditions when the grab sample is taken.

Results: It is expected to observe the following results:

1. The maximum temperature of the residues with supply of water as the high lime undergoes the hydration process.

2. The rates of the temperature rise (heat generation).

3. Permeability at unsaturated conditions.

4. Permeability at saturated conditions.

5. A method of controlling the hydration process, or a recommendation of slaking lime, then column operations.

Benefits:

1. Better understanding the characteristics of the AFBC/SATR residues and AFBC residues.

2. Saving expenses and time from future column operations with the AFBC residues.

Duration: Approximately 6-8 weeks.

Note: This experiment and the particulate control experiment will be coordinated to use time effectively.

PLEXIGLAS SQUARE COLUMN SKETCH